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PRINCIPLES FOR IMPROVING STRUCTURAL CRASH WORTHINESS FOR STOL AND CTOL AIRCRAFT

By

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June 1966

U. S. ARMY AVIATION MATERIEL LABORATORIES
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This report was prepared by Aviation Safety Engineering and Research (AvSER), a division of Flight Safety Foundation, Inc., under the terms of Contract DA 44-177-AMC-254(T). This effort consisted of the investigation, through dynamic testing, of the effectiveness of minor structural modifications in improving crashworthiness, with the objective of evolving design principles and/or concepts that would contribute to a more crashworthy design.

The results of this study indicate various methods of improving the crashworthiness of Army aircraft. Several approaches offering promise for advancement in this area are recommended for further investigation.

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FOR STOL AND CTOL AIRCRAFT

Technical Report
AvSER 65-18

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SUMMARY

The area of crash behavior analysis of aircraft structures is investigated.
The investigation begins with the definition of two indices of crashworthiness of basic aircraft structures and the analysis of the influence of several general types of structural modifications upon these two indices.
This analysis, using fundamental principles of mechanics, contains several simplifying assumptions, which are explained as they are introduced.

Design concepts to improve the ability of the "protective container" to maintain living space for occupants during a crash or to attenuate the accelerations experienced by occupants during a crash are developed for crash conditions which are either primarily longitudinal in nature or primarily vertical in nature. Analytical methods are then provided to show how and when to apply these design concepts to any particular aircraft.

The principles which are presented are suitable for use during design of new aircraft as well as modifications of existing aircraft.

The results are presented from three full-scale crash tests of small twin-engine airplanes which were conducted as a part of this investigation.

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ILLUSTRATIONS

SYMBOLS

Mass, slugs . . . . M

Velocity, fps V

Energy, ft-lb . . . . U

Force, lb . . . . F or P_{av}

Time, sec . . . . t

Differential Time . . . . dt

Ratio of Any Acceleration to the
Acceleration Due to Gravity . . . . G

Acceleration, ft-sec . . . . a

Deformation Distance, ft . . . . x or s

Proportionality Constants . . . . K

Subscripts

Aircraft . . . . A

Initial Condition . . . . o

Final Condition . . . . f

Ground or Soil . . . . G

Structural . . . . S

Average . . . . av

Cabin C

Earth . . . . E

BACKGROUND AND OBJECTIVES

BACKGROUND

In recent years a growing interest in the reduction of unnecessary injuries and fatalities resulting from aircraft accidents has been evidenced by an increased research activity in this area. The U. S. Army has been particularly active in such efforts, and measurable progress has been achieved in certain specific areas. This report is concerned with advancing this general effort in the particular area of airframe design. Analysis of accident experience indicates that crash survival is influenced largely by five general survivability factors, which may be described briefly as follows:

1. Postcrash Hazard--The threat to life posed by fire, drowning, exposure, etc., after the completion of the impact sequence.

2. Tiedown Chain Strength--The strength of linkage preventing occupant, cargo, or equipment from becoming missiles during the crash sequence.

3. Crashworthiness of Aircraft Structure--The ability of the "protective container" to maintain living space for occupants during a crash.

4. Occupant Acceleration Environment--The intensity and duration of accelerations experienced by the occupants (with tiedown assumed intact) during the crash.

5. Occupant Physical Environment--The extent of lethal projections or barriers in the immediate vicinity of the occupant, which may present contact injury hazard.

Much effort has been directed toward the improvement of aircraft seats and restraint systems, thus advancing the study of tiedown chain strength. Likewise, the factors of postcrash hazard and occupant physical environment have received attention with encouraging results. However, a research effort of comparable scale has not previously been undertaken in the area of crash behavior analysis of aircraft structure. Such a study hopefully could lead to improvements in both structural crashworthiness and occupant acceleration environment, through minor changes in structural design. Additionally, further knowledge of force transmission and acceleration distribution characteristics would provide support to the continuing tiedown strength studies.

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Consequently, in order to broaden the scope of the crash survival study program, the U. S. Army Aviation Materiel Laboratories (formerly the Transportation Research Command) has initiated a project to develop crashworthiness design principles applicable to all types of U. S. Army aircraft and to demonstrate improvements that can be obtained from minor alterations of structural design. Analysis and experimental work supporting this program have been undertaken by Aviation Safety Engineering and Research, a Division of Flight Safety Foundation, Incorporated (AvSER).

OBJECTIVES

The specific objectives of this investigation are:

1. To determine the influence of airframe structural characteristics on overall aircraft crashworthiness.

2. To determine the effectiveness of minor structural modifications in improving crashworthiness.

3. To evolve design principles and/or concepts that would contribute to crashworthy design.

4. To develop recommendations for further investigations that offer promise of advances in this area.

ANALYSIS OF FACTORS INFLUENCING CRASH BEHAVIOR

To achieve the outlined objectives, an analysis of several factors pertinent to structural crashworthiness has been developed and is presented in this report. The analysis, employing fundamental principles of mechanics, is designed to treat gross behavior of the structure. Simplifying assumptions have been made and are discussed as they are introduced.

DEFINITION OF "CRASHWORTHINESS INDICES"

In order to conduct a meaningful program aimed at improving the overall structural crashworthiness, a means of measuring crashworthiness is essential. Two indices of crashworthiness which have been proposed in an earlier report[1] are:

1. The degree of cabin collapse under standard crash conditions (chosen through consideration of aircraft operating characteristics).

2. The level of acceleration experienced by occupants during the crash.

The indices reflect the influence of structural considerations upon two of the five outlined survivability factors: the integrity of the "protective shell" and the occupant acceleration environment.

STRUCTURAL MODIFICATIONS CONSIDERED

Acceptance of the proposed indices as structural crashworthiness criteria permits a comparative crashworthiness study of various structural configurations subjected to similar crash conditions and leads to the consideration of structural modifications that offer promise of improved probability of occupant survival in aircraft accidents. These include:

1. Increase in the energy absorption capacity of the structure forward of the passenger cabin to provide added protection for the cabin.

2. Alteration of the structure which makes initial contact with the ground to reduce gouging and scooping of soil, hence lowering accelerations and transmitted forces.

3. Reinforcement of cockpit and cabin structure to enable it to withstand greater transmitted forces.

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4. Modification of wing and empennage structure to insure that these parts break away during a crash, to effect a reduction in the mass of the aircraft, hence reducing the requirement for energy absorption in cabin structure as well as reducing the forces to be withstood by cabin structure.

5. Modification of fuselage structure to allow increased deformation or collapse of structure in unoccupied regions, thus permitting additional structural energy absorption.

To determine the potential contributions of each of the five areas of modifications listed above, an understanding is required of the influence of controllable factors. In particular, an insight is needed into the influence of (1) structural energy absorption, (2) the earth gouging and scooping phenomena, and (3) change in effective aircraft mass upon the selected crashworthiness indices.

THE INFLUENCE OF ENERGY ABSORPTION

The influence of structural energy absorption upon degree of cabin collapse and upon occupant acceleration has been discussed (employing simplified mathematical models) in an earlier report.[1] A summary of the development relationships is presented below for the purposes of the current analysis.

From a consideration of conservation of energy, the initial kinetic energy of an impacting aircraft must be accounted for in energy "dissipated" (in the form of heat) during the deformation of both soil and structure. Therefore,

$$\frac{M_A(V_o^2 - V_f^2)}{2} = U_G + U_S \tag{1}$$

where

M_A = Mass of aircraft, slugs

V_o = Initial (impact) velocity, fps

V_f = Velocity remaining after impact, fps

U_G = Energy dissipated in soil deformation and ground friction, ft-lb

U_S = Energy dissipated in structural deformation, ft-lb

As a simplified model, the structural deformation energy, U_S, may be expressed as

$$U_S = P_{av}s + U'_S + U_C \qquad (2)$$

where

P_{av} = Average force developed in collapse of structure forward of cabin, lb.

s = Linear deformation distance (reduction in length) of the structure forward of cabin, ft.

U'_S = Deformation energy in structure other than in cabin or structure forward of cabin, ft-lb.

U_C = Energy to be absorbed in cabin deformation, ft-lb.

The cabin deformation energy, U_C, may be obtained from equations (1) and (2), and is

$$U_C = \left[\frac{M_A(V_o^2 - V_f^2)}{2} - U_G \right] - (P_{av}s + U'_S). \qquad (3)$$

This equation for cabin deformation energy is valid if conditions reach or exceed the point of onset of cabin deformation.

Several useful observations may be made from expression (3). Assuming, for the present, a fixed mass and velocity and ignoring control over energy dissipated exterior to the aircraft, the factors that are controllable are P_{av}, s, and U'_S.

Consequently, the energy which must be absorbed in cabin collapse may be reduced by

1. Increasing P_{av}, the average crushing force acting upon the forward structure. P_{av} may be increased for a given maximum collapse force by maintaining as near a uniform force as possible during collapse. Additionally, P_{av} may be further increased by admitting an increase in the maximum force applied to the forward structure. This latter option is limited, however, by the existing strength of the cabin. If, for example, the maximum collapse force for forward structure were to exceed the

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cabin critical force, * then the energy absorption objective would be defeated, as the cabin deformation would commence prior to full collapse of forward structure and therefore prior to full energy dissipation in the forward structure.

A further point to be considered is the effect of forward structural modifications upon the second crashworthiness index, occupant acceleration. If the maximum collapse force were increased, the aircraft acceleration would increase, adversely affecting this second index. A trade-off in effect upon the two indices must therefore be considered.

2. Increasing the available deformation distance, s, which would also permit greater energy absorption in the forward structure. (This could be accomplished without increasing the maximum collapse force.) This factor is usually not controllable by simple modification but should definitely be considered in original design. This could be accomplished, for example, by placing the cabin as far aft as practical.

3. Increasing the deformation energy absorbed in aircraft structure other than forward structure or cabin. This would further contribute to a lower cabin deformation energy requirement. Modifications which reduce collapse loads to permit plastic deformation at selected points could accomplish this.

THE INFLUENCE OF EARTH GOUGING AND SCOOPING

Under certain conditions of impact and structural deformation, the forward sections of an impacting aircraft deform to become a scoop, picking up a mass of earth and "driving" it to the velocity of the aircraft. This is accomplished in a very short time interval; therefore, the principle of conservation of momentum may be applied to the system, which includes the aircraft mass and the effective mass of the soil. Accordingly, conservation of mementum leads to

$$M_A V_o = (M_A + M_E) V \qquad (4)$$

where

$$M_A = \text{Mass of aircraft, slugs}$$

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*Cabin critical force - the force required to cause onset of collapse of cabin structure.

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M_E = Effective mass of accelerated earth, slugs

V_o = Initial (impact) aircraft velocity, ft per sec

V = Velocity of combined system immediately after impact, ft per sec

Solving equation (4) for V, we obtain

$$V = \left(\frac{M_A}{M_A + M_E} \right) V_o. \tag{5}$$

To find the interaction force involved in the momentum exhange, an impulse-momentum relationship may be applied to the earth mass as a free body:

$$\int_0^{\Delta t} F \, dt = M_E V \tag{6}$$

where

F = Interaction force, lb

Δt = Time interval required for momentum exhange, sec

By definition,

$$\int_0^{\Delta t} F \, dt = F_{av} \Delta t. \tag{7}$$

Substituting equations (5) and (7) into equation (6) yields

$$F_{av} = \left(\frac{M_A M_E}{M_A + M_E} \right) \frac{V_o}{\Delta t}.$$

Consequently, the average acceleration of the aircraft mass due to the acceleration of a mass of earth is

$$\frac{F_{av}}{M_A} = a_A = \left(\frac{M_E}{M_A + M_E} \right) \frac{V_o}{\Delta t} \tag{8}$$

If the distance, x, traveled by the aircraft during the interval of momentum exchange were essentially constant, then the time interval, Δt, would be inversely proportional to the velocity at impact; that is,

$$\Delta t = K \frac{\Delta x}{V_o} \ .$$

Therefore,

$$a_A = \left(\frac{M_E}{M_A + M_E}\right) \frac{V_o^2}{K \Delta x} \ , \tag{9}$$

which indicates that the deceleration of the impacting aircraft varies with the velocity squared (where the scoop effect is a dominant factor). Thus, at high impact velocities, the scoop phenomenon assumes a greater significance.

A numerical example would serve to lend quantitative character to the discussion.

If the following conditions exist,

$$V_o = 140 \text{ feet per second}$$

$$\Delta t = 0.02 \text{ second}$$

$$M_E = 0.185 \ M_A,$$

then

$$a_A = \left(\frac{M_E}{M_A + M_E}\right) \frac{V_o}{\Delta t}$$

$$= \left(\frac{0.185}{1.185}\right) \frac{140}{0.02}$$

$$a_A = 1092 \text{ feet per second}^2 = 34G.$$

If impact velocity, V_o, and time, Δt, remain unchanged but the effective earth mass, M_E, is reduced to $0.10\, M_A$, the average impulse accelerating the aircraft becomes

$$a_A = \left(\frac{0.1}{1.1}\right)\left(\frac{140}{0.02}\right) = 637 \text{ feet/second}^2 = 19.8G.$$

Increasing the impact velocity, V_o, to 160 feet per second (under the aforementioned assumption that acceleration varies with velocity squared) when $M_E = 0.185\, M_A$ results in an aircraft acceleration of

$$a_A = \left(\frac{160}{140}\right)^2 1092 = 1430 \text{ feet/second}^2 = 44.5G.$$

And if a mass of earth equal to $0.10\, M_A$ is accelerated under an impact velocity of 160 feet per second, the average acceleration is computed to be 25.8G.

Figure 1 shows a family of curves relating impulsive aircraft acceleration to the ratio of effective earth mass to aircraft mass for various impact velocities.

In addition to the force associated with momentum exchange, soil penetration by structural projectiles gives rise to a "drag" force sometimes called the "plowing effect". This force adds to other soil reactive forces. The plowing force should be distinguished from the discussed impulsive force associated with momentum exchange, in that the former is a steady-state force depending upon velocity, soil shear strength, and projected area of interference. It should be noted, however, that any modification serving to reduce scoop effect also helps to reduce the plowing effect contribution.

INFLUENCE OF AIRCRAFT MASS

As suggested earlier, it is possible to reduce the aircraft mass through planned breakaway of portions of the aircraft during a crash. An analysis of the influence of the reduction of aircraft mass is presented here.

The expression for cabin deformation energy, U_C, which was obtained from a solution of equations (1) and (2) is repeated below.

$$U_C = \left[\frac{M_A (V_o^2 - V_f^2)}{2} - U_G\right] - \left(P_{av} s + U_S'\right) \qquad (3)$$

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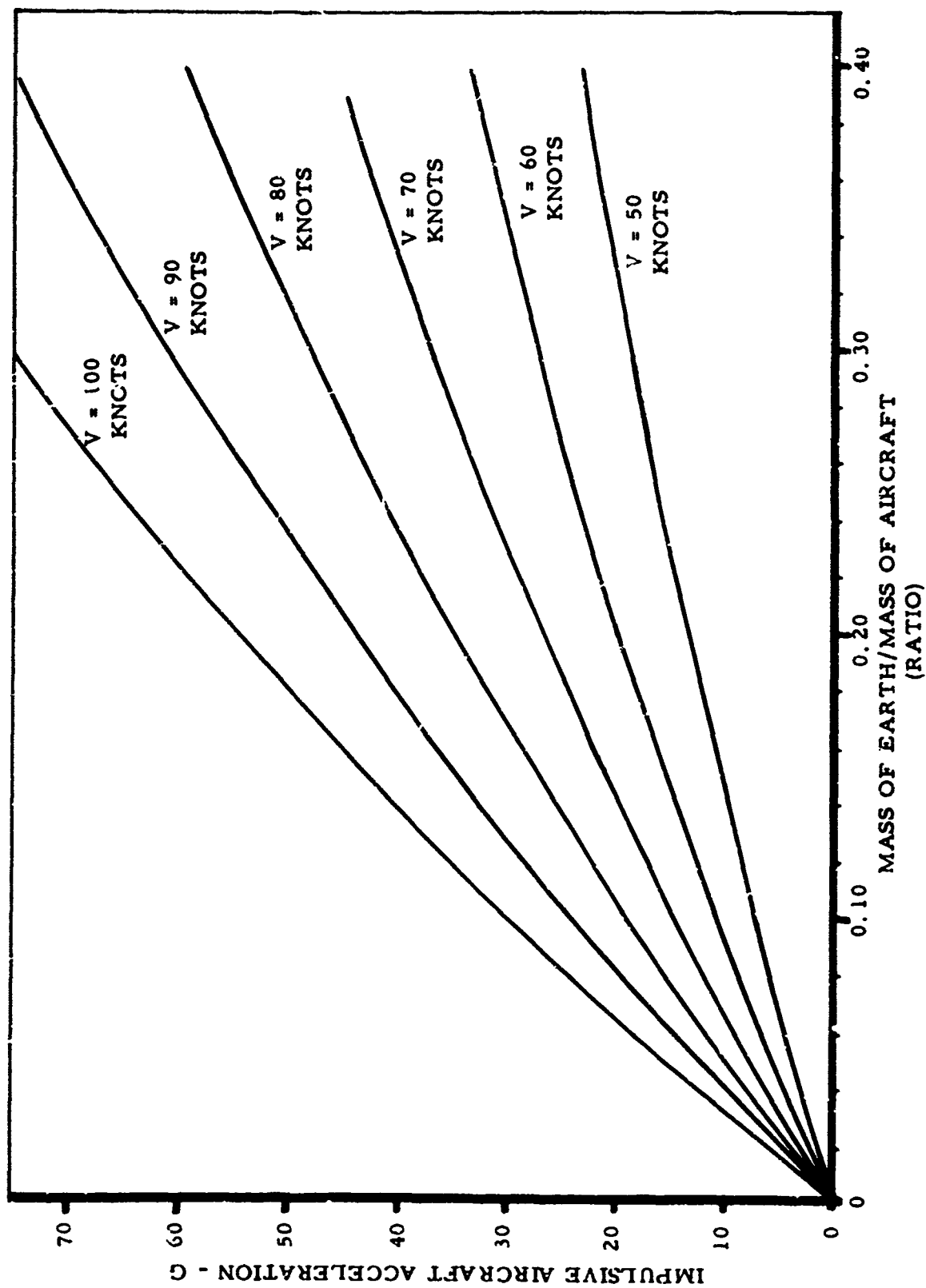
Figure 1. Impulsive Aircraft Acceleration as a Function of Velocity and Ratio of Accelerated Mass of Earth to Aircraft Mass. (Based upon assumed time, Δt, for acceleration of earth mass.)

Changes in effective aircraft mass during a crash would leave the energy absorbed in collapse of forward structure, $P_{av}s$, and the energy absorbed in plastic deformation of other aircraft structure, U'_S, essentially unaffected. The energy dissipated exterior to the aircraft in deformation of soil, U_G, would, on the other hand, be influenced by the aircraft mass. This soil deformation energy assumes several forms: principally, the energy associated with superficial friction and that involved in the plowing and scooping of soil.

With a reduced aircraft mass, contact forces would tend to be less, and energy dissipated in friction would be reduced. Also, with reduced aircraft mass (assuming the force transmitted through deforming structure to be controlled by structural collapse strength and therefore constant with respect to mass change), less time would be required to accomplish a given velocity change. This would allow less time to dissipate energy in soil deformation.

Consequently, a reduction in mass of the aircraft would also serve to reduce the energy absorbed at or within the ground. As a plausible approximation, in the absence of a developed soil dynamics study, the magnitude of U_G is assumed to be proportional to the aircraft mass.

Denoting by M_A' the effective aircraft mass after breakaway of portions of the aircraft, an expression may be written for the cabin deformation energy with reduced mass:

$$U_C = \left[\frac{M_A'}{M_A} \quad \frac{M_A (V_o^2 - V_f^2)}{2} - U_G \right] - (P_{av}s + U'_S) \quad (10)$$

where U_G denotes the soil deformation energy obtainable without reduction in mass.

A hypothetical numerical example may serve to illustrate the influence. In this case it is assumed that the soil deformation energy for a given accident environment is equal to 70 percent of the initial kinetic energy or

$$U_G = 0.7 \left[\frac{M_A (V_o^2 - V_f^2)}{2} \right].$$

Then equation (10) becomes

$$U_C = \frac{M_A'}{M_A} \left[0.15 M_A (V_o^2 - V_f^2) \right] - \left(P_{av} s + U_S' \right)$$

and for the following impact conditions,

Airplane weight = 8000 pounds

M_A = 250 slugs

V_o = 140 feet per second

V_f = 80 feet per second

$P_{av} s$ = 300 x 10³ foot-pounds

U_S' = 50 x 10³ foot-pounds.

The cabin deformation energy is

$$U_C = \left[\frac{M_A'}{M_A} (495 \times 10^3) - 350 \times 10^3 \right] \text{ ft-lbs.}$$

Consequently, if there is no reduction of the mass of the aircraft during the crash, the cabin deformation energy is

$$\underline{\underline{U_C = (145 \times 10^3) \text{ ft-lbs.}}}$$

For a mass reduction of 0.85 of the original mass, the requirement for cabin deformation energy is reduced to

$$(U_C)_{0.85 M_A} = \left[0.85 (495 \times 10^3) - 350 \times 10^3 \right] \text{ ft-lbs}$$

$$(U_C)_{0.85 M_A} = \underline{\underline{70 \times 10^3 \text{ ft-lbs}}} .$$

This illustrates the reduction of cabin deformation energy which is possible through a small reduction of aircraft mass.

DESIGN CONCEPTS OFFERING POSSIBLE
IMPROVED CRASHWORTHINESS

In the foregoing discussion, five areas of structural modification were listed which offer promise of improved occupant survival in aircraft accidents:

1. Increase in energy absorption capacity of structure forward of occupiable area.

2. Alteration of structure to reduce scooping and gouging of soil.

3. Reinforcement of cabin structure.

4. Modification of wing and empennage structure to insure breakaway during a crash.

5. Modification of structure to permit increased deformation in unoccupied areas.

As these five types of modifications indicate, improvement of crash-worthiness through structural modification is accomplished through improvement in either one or both of two survivability factors: the ability of the "protective container" to maintain living space for occupants during a crash or the attenuation of accelerations experienced by the occupants during a crash.

When considering any design concept for improving structural crash-worthiness, the survivability factor to be improved must be kept in mind, and, additionally, the energy absorption characteristics of the crash must be understood.

There is a basic difference between the absorption of kinetic energy in crashes which are primarily longitudinal and those which are primarily vertical. In longitudinal impacts a high percentage of the initial kinetic energy of the aircraft is dissipated in compression and acceleration of masses of earth and in friction between the aircraft and the earth. Consequently, in the longitudinal crashes a relatively low percentage of the initial kinetic energy is absorbed by structural deformation. In primarily vertical impacts, on the other hand, much more of the initial kinetic energy must be absorbed by the structure.

This leads to separate consideration of deisgn concepts for improving crashworthiness under primarily longitudinal impact conditions and

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under primarily vertical impact conditions. The concepts which will be discussed in this report are directed toward all types of aircraft, but are not in general readily applicable to large transport airplanes.

IMPROVEMENT OF CRASHWORTHINESS IN LONGITUDINAL IMPACTS

Since in primarily longitudinal crashes the compression and scooping of earth contribute so heavily to the accelerations experienced, our first step will be to discuss methods of reducing these factors.

When the forward sections of an impacting aircraft deform so that an earth scoop is formed and earth is impulsively accelerated, two adverse effects may be encountered. First, excessively high acceleration of the entire airplane may occur. Second, the high forces required to accelerate the earth mass may be concentrated in a small area, causing local collapse of forward cockpit structure with a resulting encroachment upon the occupant "protective shell". Reduction of earth scooping, then, can conceivably bring about direct improvement of both survivability factors: the ability of the protective container to remain intact and the level of accelerations encountered by occupants in a crash.

Reduction of earth scooping can be accomplished by structural modification which reduces the presentation of abrupt surfaces which can readily gouge and dig into impact surfaces. The modifications must be designed to provide a large, relatively flat surface to allow impacting structure to skid along on top of the impact surface rather than dig into it. These modifications, then, must prevent impact damage which exposes such structure as the strong, vertical forward cockpit bulkhead or firewall. The lower nose structure forward of this bulkhead or firewall must provide the skidding surface.

Consequently, the effective method of modification involves local strengthening of the lower nose structure to prevent its "snapping inward" under impact loading (in the manner of a shallow spherical shell "snapping through" under excessive uniform loading) and to improve its capability in providing a flat skidding surface. The nose structure should be modified to resist vertical loading. When excessive loading is encountered, failures should occur through crushing of local structure instead of general buckling. One method of accomplishing this local reinforcement is shown in the sketch of Figure 2. It may be noted that the modification shown does not necessarily increase the longitudinal strength of the nose section, but is aimed at reducing deformation due to vertical loads distributed over the lower nose surface.

If this modification is to be effective, the lower skin must be made of
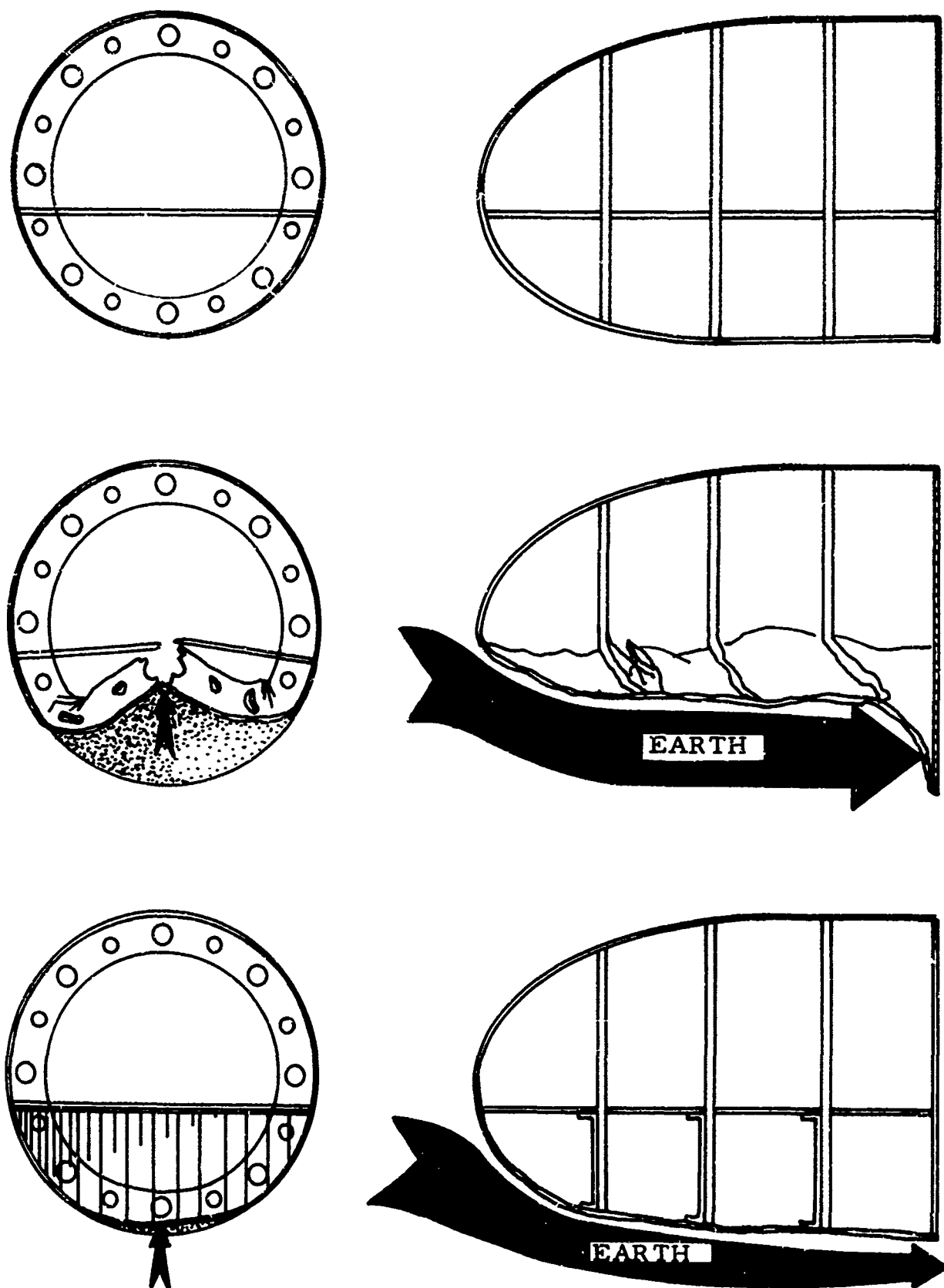
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Figure 2 . Method of Reinforcing Nose Structure To Provide Increased
Resistance to Vertical Loads and Reduce Earth Scooping.

ductile material, thick enough to resist the friction forces of impact. The skin must remain continuous to present a skidding surface and protect against earth scooping.

Often, in aircraft with the engine mounted in the nose, structural bracing as discussed above is not practical because the section below the engine is very light secondary structure made up of removable doors and cowling. The engine and engine mounts, however, are strong and could support a skidding surface if a filler were provided between the engine and the lower skin. The filler could be made of lightweight plastic foam or honeycomb material, contoured to fit the lower surface and fill as much space as possible between the skin and the engine. The attachments of such removable access doors and cowling should be strong and reliable even when considerably deformed.

In multiengine aircraft, the engine nacelles may present as much of an earth scoop as the nose of the fuselage, and, since the engines are often attached to the strong, rigid wing center section, the forces produced by engine earth scooping are transmitted to the fuselage and occupiable area. Use of the modification methods just discussed can be helpful in reducing the harmful contribution of engine earth scooping.

The experimental results presented in the appendix show that longitudinal accelerations produced by earth scooping can be significantly reduced by simple modification of structure.

Many longitudinal crashes involve a rapid change in pitch attitude to quickly align the aircraft fuselage with the impact surface. The resulting angular acceleration produces a fuselage bending moment which usually tends to produce compression of upper fuselage members. This compression is combined with compression of the fuselage due to the longitudinal forces of impact. The result is compressive buckling failure of fuselage structure. When the failure occurs at an occupiable location along the fuselage, the passenger "protective container" is compromised.

It is possible to strengthen fuselage structure enough to prevent this compressive failure. The practicality of such a modification, however, depends upon the length of the fuselage and the degree to which it lacks sufficient strength. Long fuselages or very weak fuselages* may

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*These terms, as used here, refer to the occupiable portion of the overall fuselage. Compressive failures outside the occupiable section would have no direct adverse influence on occupant survival.

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require such massive addition of strength as to be impractical due to weight increase, or the modification required may be so complex as to be unfeasible. In such cases, where simple modification can not offer an appreciable increase in crashworthiness, it is desirable to determine the probable failure points and to position passengers away from those locations to minimize the risk of injury in a crash. For other aircraft, simple modifications to increase the compressive strength of upper fuselage structure can result in prevention of failure or relocation of probable failure points to unoccupied portions of the fuselage.

CUTAWAY VIEW

REINFORCEMENT

FRONT VIEW   SIDE VIEW

REINFORCEMENT
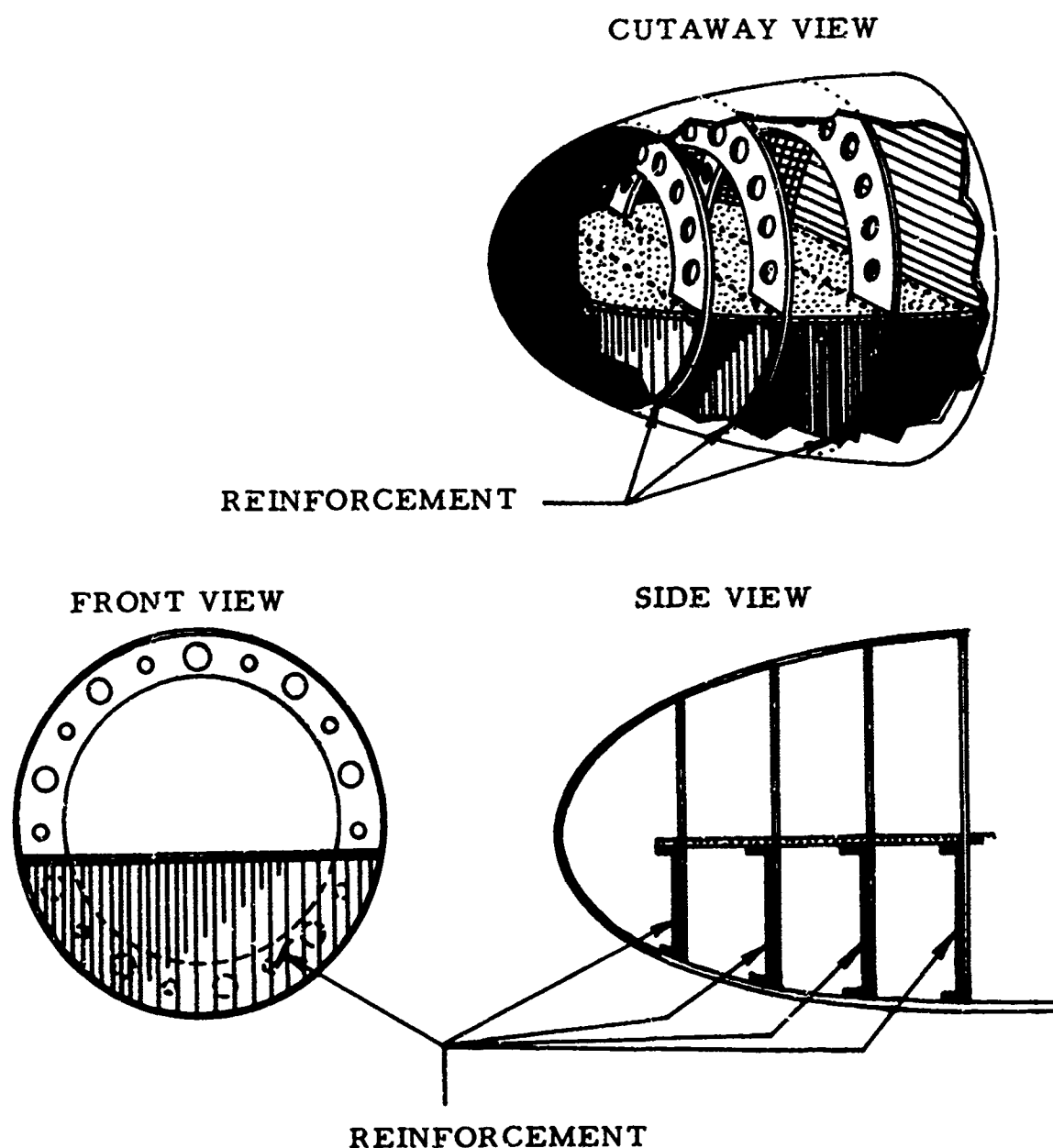
Figure 3. Method of Modification of Nose Structure To Reduce Earth Scooping, Similar to Experimental Modification Tested in Full-Scale Crash Test.

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UNMODIFIED CONFIGURATION

MODIFICATION OF FIREWALL TO
REMOVE THE ABRUPT SURFACE

ADDITION OF ENERGY ABSORBING
FILLER TO PREVENT SCOOP FROM
DEVELOPING UNDER IMPACT FORCES

Figure 4 .   Two Methods of Reducing Earth Scooping in Engine Mount-
ing Areas.

Determination of probable locations of fuselage buckling failures result-
ing from the bending loads of longitudinal impacts is simplified by the
following assumptions:

1.   The airplane is treated as a rigid body.

2.   The force of impact which produces pitch change (and
fuselage bending loads) is a concentrated load of constant
magnitude.

3. Upon impact, the aircraft rotates about an instantaneous center of rotation which is not located at the aircraft center of gravity.

Using these assumptions, the location of probable failure points is relatively straightforward. For nose-first impacts, the following steps lead to the determination of points of probable failures and provide quantitative information for modifications to strengthen cabin structure:

1. Determine the pitching moment of inertia for the airplane about the aircraft center of gravity at impact.

   The moment of inertia should include the effects of all elements which are part of the aircraft or which are aboard the aircraft at initial impact.

2. Determine the nose crushing force and its line of application.

   The magnitude of the nose crushing force may be estimated by either of two methods:
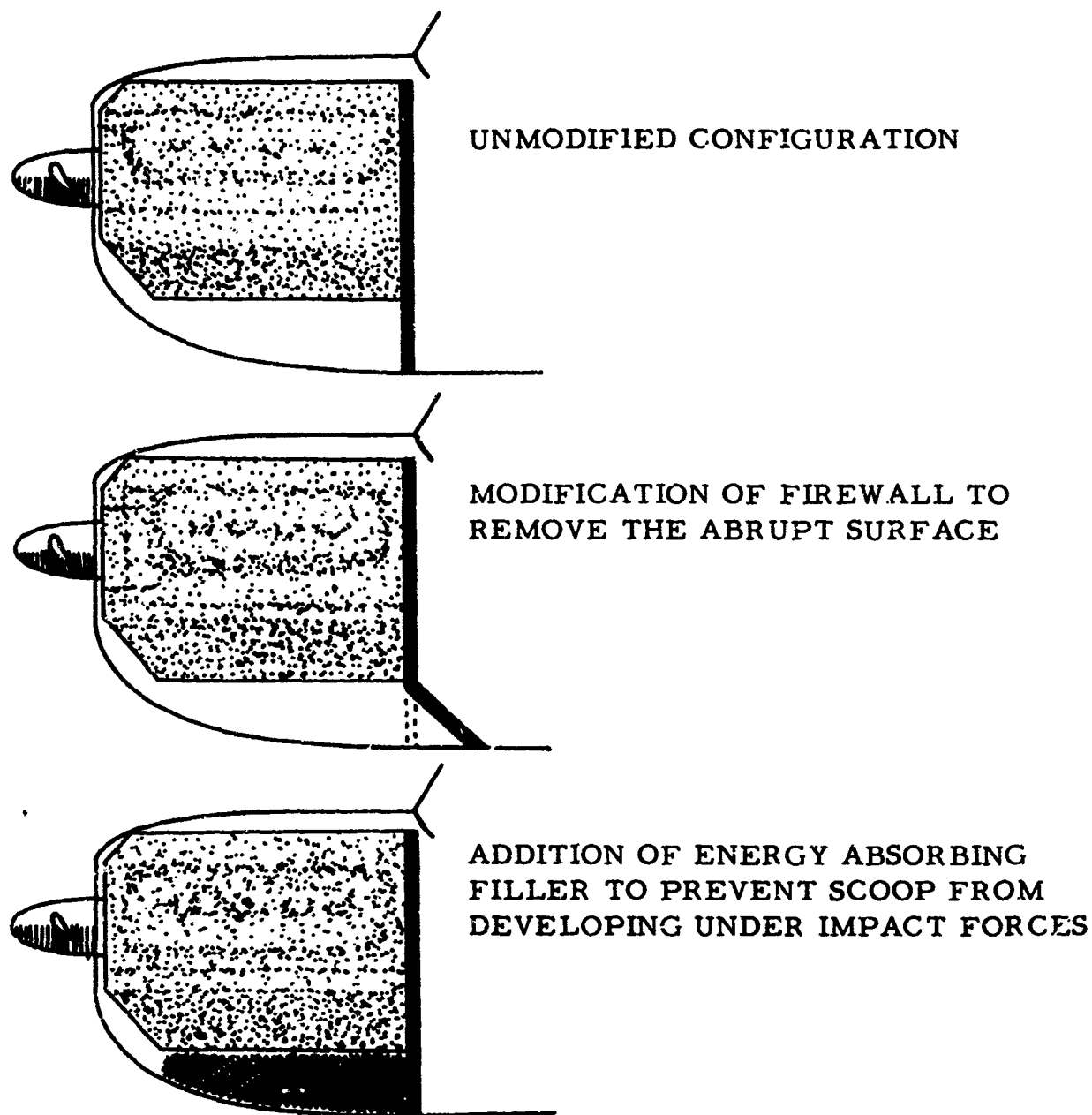
   a. The crushing load for impacting structure may be calculated using static strength data. (This method is often limited by the lack of understanding of strength and behavior of materials in the plastic range of stress.)

   b. The time allowed to rotate the aircraft through an angle equal to the impact angle may be computed. This time can then be used to determine the magnitude of angular acceleration necessary to produce the pitch change. An approximate force may then be determined using the expression

$$F \text{ (lb)} = \frac{a \, I}{r}$$

where

a = Angular acceleration, rad/sec^2

I = Pitching moment of inertia, slug-ft^2

r = Distance from point of application
of force to aircraft center of gravity, ft.

The force, which is important for further use in determining
failure points, is the component of the impact force perpend-
icular to the aircraft longitudinal axis. The line of action of
the force should be a line perpendicular to the aircraft long-
itudinal axis passing through the approximate center of impact
forces.

3. Determine the location of the instantaneous center of rotation.

The instantaneous center of rotation is found, using the quan-
tities generated in step 1 and step 2 above, from the following
relationship (reference Figure 5):

$$L \text{ (ft)} = \frac{(k_{c.g.})^2 + r^2}{r}$$

where

L = Distance from point of application of impact
force to center of rotation, measured parallel
to aircraft longitudinal axis, ft

r = Distance from point of application of impact
force to aircraft center of gravity, also measured
parallel to aircraft longitudinal axis, ft

$k_{c.g.}$ = Radius of gyration of aircraft mass with respect
to aircraft center of gravity, ft

$$(k_{c.g.})^2 = \frac{I_{c.g.}}{M}$$

$I_{c.g.}$ = Pitching moment of inertia about
center of gravity, slug-ft

M = Aircraft mass, slugs.

Notice that the location of the center of rotation is dependent
only upon the distance between the applied load and the center
of gravity and the magnitude of the pitching moment of inertia
divided by the aircraft mass. The magnitude of the impact
force need not be considered.

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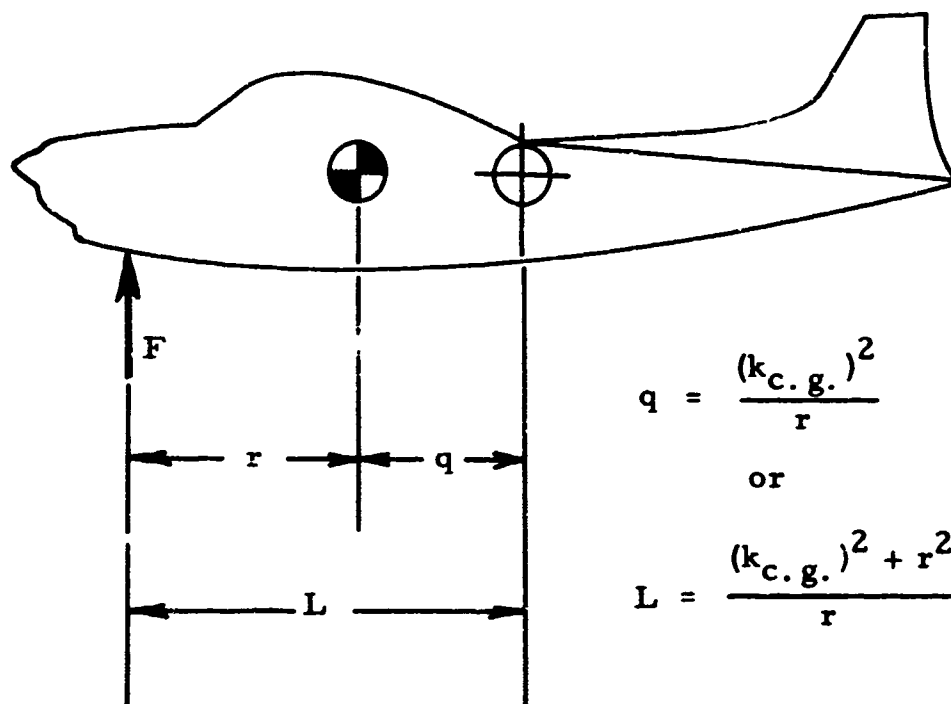
$$q = \frac{(k_{c.g.})^2}{r}$$

or

$$L = \frac{(k_{c.g.})^2 + r^2}{r}$$

Figure 5. Determination of Instantaneous Center of Rotation

4. Determine the angular acceleration of the aircraft, for rotation about the center of gravity, under action of the crushing force determined in step 2.

5. Obtain the longitudinal distribution of airplane dead weight for the initial impact configuration.

6. Determine the longitudinal shear load distribution resulting from the application of the impact force plus mass times acceleration forces resulting from the angular acceleration found in step 4.

   For determination of the tangential accelerations necessary to find the mass times acceleration forces to be used in shear distribution, rotation is considered to occur about the instantaneous center of rotation.

7. Find the bending moment distribution resulting from the shear loading found above.

8. Plot the applied bending moment distribution obtained in step 7 against fuselage station.

9. On the same chart used to plot the applied bending moment distribution (step 8), plot fuselage bending strength distribution against fuselage station.

10. From the chart drawn in step 8 and step 9, determine the locations where the applied bending moment exceeds the fuselage bending strength by the greatest margin. These are locations of probable initial fuselage collapse.

In addition to showing the locations of probable initial fuselage collapse, the chart of fuselage bending strength and applied bending moments can be used to determine the amount of strengthening necessary to prevent the occurance of collapse within the occupiable section of the airplane.

Also, the difference between applied loads and fuselage strengths can show if it is possible, with consideration of flight load requirements, to reduce the fuselage strength to insure failure of the fuselage in an un-occupiable location under crash loading.

The use of the plotted curves of applied bending moment and fuselage bending strength is illustrated in Figure 6.

Two approaches have now been discussed, leading to realistic structural modifications to improve structural crashworthiness. The discussion has indicated methods of

1. Reducing impulsive scooping of earth

2. Reinforcing cabin structure to prevent its collapse within occupiable areas

3. Determining practicality of reducing strength of fuselage structure to insure failure in unoccupiable areas

4. Reducing strength of fuselage structure to increse deformation and energy absorption in unoccupiable area

The remaining area of promise in improving crashworthiness, the im-provement of energy absorption characteristics for structure forward
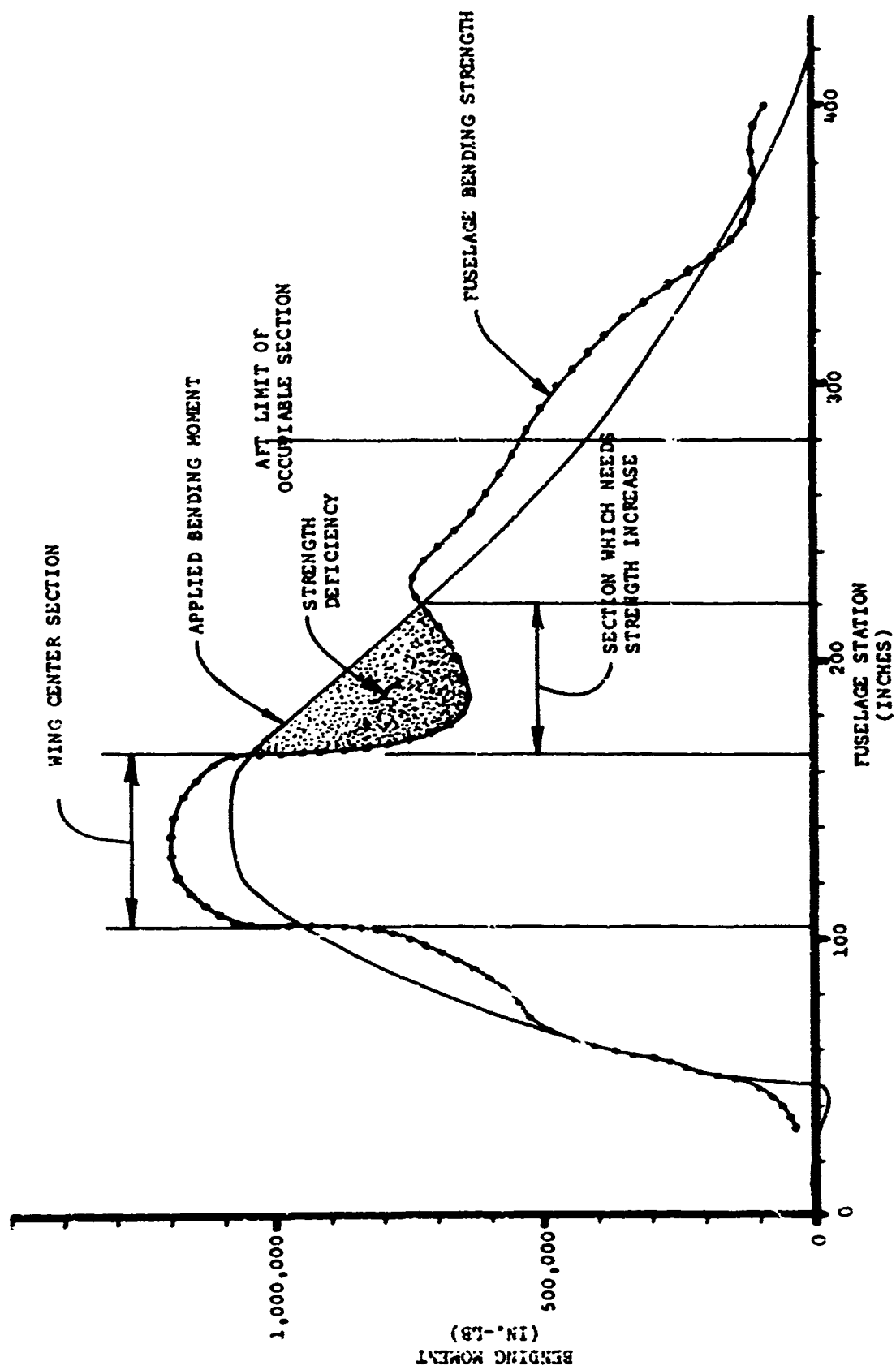
Figure 6. Comparison of Fuselage Bending Strength and Applied Bending Moment.

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of the occupiable area, has been discussed earlier during the discussion of the influence of controllable factors and need not be discussed further here.

IMPROVEMENT OF CRASHWORTHINESS IN VERTICAL IMPACTS

As has been indicated earlier, for a primarily vertical impact (or for the vertical component of any impact), structural energy requirements differ appreciably from those of a longitudinal impact. In a vertical impact, there exists no possibility of low force level (and hence low acceleration level) energy absorption exterior to the aircraft comparable to the frictional energy absorption in a longitudinal skid. The velocity change in the vertical direction must be accomplished in a short time interval. Consequently, when the vertical energy level is high, crashes are generally characterized by significant structural deformation and high accelerations at aircraft floor level.

Previous studies have treated methods of reducing the effects of the high floor accelerations upon occupants. These studies have resulted in recommendations for providing energy absorbing passenger and crew seats to protect occupants in crashes at energy levels which experience has shown are survivable from the standpoint of general cabin collapse.

In order to evaluate potential improvements in crashworthiness of cabin structure for vertical impacts, two idealized extreme configurations are presented below that serve to point out problem areas.

First consider a fuselage section in which the aircraft mass is concentrated at the top of a fuselage section which behaves as a nonlinear spring. This is schematically illustrated in Figure 7.

Moreover, assume that the "spring" is initially elastic and remains so for a moderate deformation; thereafter, the spring force reaches a critical value that produces a plastic collapse of the support structure.

For such a model, a vertical impact would require that substantially all of the kinetic energy of the mass be converted to deformation energy of the structure. If this kinetic energy were too great, deformation would proceed to collapse of the structural support, or cabin collapse.

This model of the fuselage can reasonably be extended to include a crushable underside (below the cabin floor) which would deform plastically for forces below the critical load for general fuselage collapse. This crushable underside would then absorb energy along with the elastic deformation energy of the main fuselage structure, providing an increased buffer against general collapse.

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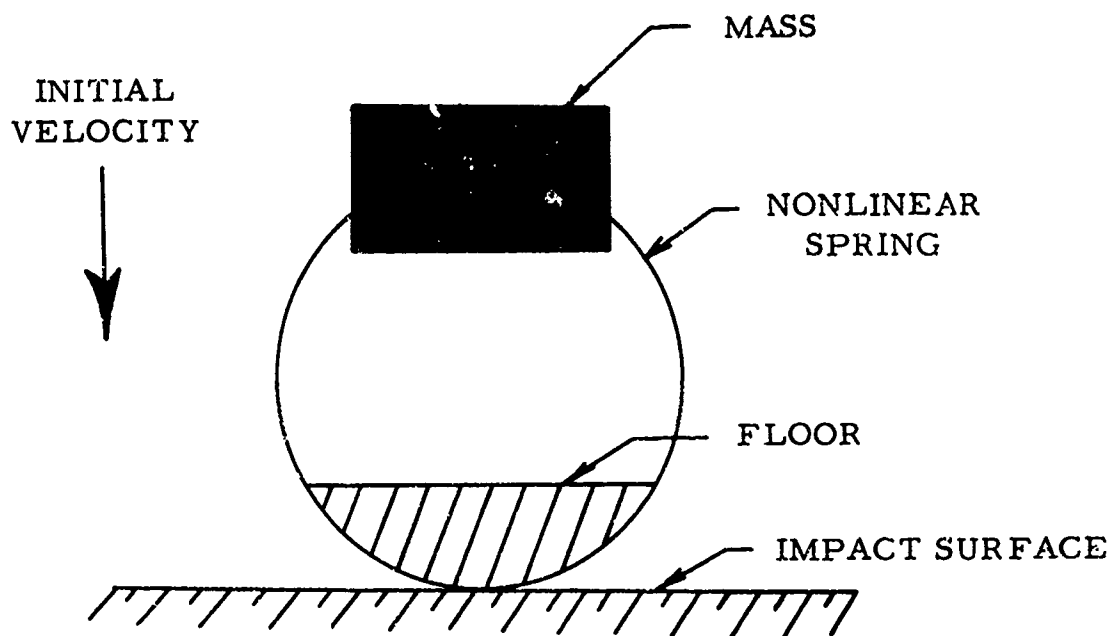
Figure 7. Schematic Diagram of Idealized Aircraft Which Has Mass
Concentrated in Upper Fuselage.

A second configuration presented as the opposite extreme fuselage model
would consist of a structure of negligible weight with the aircraft mass
concentrated at or near the bottom of the fuselage. Figure 8 illustrates
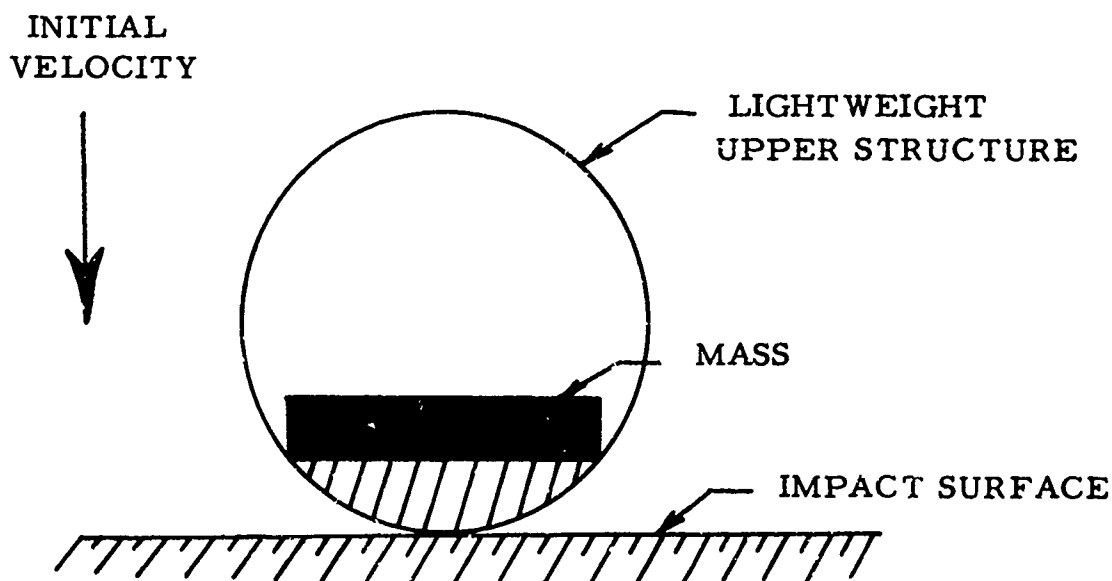this configuration schematically.

Figure 8. Schematic Diagram of Idealized Aircraft With Mass
Concentrated in Lower Fuselage.

As before, this model may be extended to include a crushable subfloor structure.

Upon vertical impact with this second configuration, without a crushable subfloor structure, the kinetic energy of the mass would be largely dissipated in the soil as an impact stress wave. The vertical stopping distance for such an impact would necessarily be short due to the small possible displacement of earth, and the magnitude of vertical accelerations at floor level would be extremely high. However, as the upper structure is light, and the danger of cabin collapse is substantially reduced, the cabin collapse force would not be reached even for high-energy impacts.

If a crushable subfloor structure is included in the model, then a sizeable portion of the kinetic energy could go into subfloor deformation. The subfloor energy absorption could serve to attenuate the floor acceleration for vertical impacts. The possibility exists for considerable energy absorption in subfloor structure.

Any realistic model is a combination of the two extreme idealizations presented above. To the extent that aircraft mass is secured to the upper fuselage, cabin collapse presents a serious problem. Also, to the extent that mass is concentrated at cabin floor level, energy absorption in the subfloor structure, and the associated acceleration attenuation, may assume significant beneficial proportions without the necessity of excessive strengthening of cabin structure to prevent its collapse.

Considering again the two proposed crashworthiness indices,

1. Extent of cabin collapse and

2. Cabin (floor) acceleration level,

an evaluation may be made of potential improvements in crashworthiness for vertical impacts.

The threat to general cabin collapse under vertical impact may be reduced in any of several ways:

First, to the extent that it is feasible, either in original design or by modification, or in cargo and equipment tiedown, a transferral of mass from the top of the fuselage to the cabin floor would be beneficial.

Secondly, a general strengthening of cabin structure may be effected

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so as to increase its resistance to vertical collapse. Localized strengthening at locations of large concentrations of mass attached to upper structure could provide largely increased resistance to general vertical collapse.

Thirdly, modifications in cabin structure that increase elastic energy absorption or provide for plastic energy absorption at loads less then the general collapse load would help to maintain the primary cabin integrity.

Finally, any increase in energy absorption in the subfloor structure realizable at load levels below the cabin collapse load would further help protect the cabin against collapse.

The threat of high vertical acceleration at the cabin floor may also be reduced through any of several methods of modification (principles of design):

A large energy absorbing stroke of the cabin floor would attenuate the average acceleration experienced at the floor for a given velocity change. This is seen from the kinematic relationship

$$V^2 = 2as \quad \text{or} \quad a = \frac{V^2}{2s}$$

where

V is the velocity change, ft per sec

a is the <u>average</u> acceleration, ft per sec^2

s is the displacement, ft.

The crushing resistance of the subfloor structure may be optimized to meet the conditions of the anticipated vertical impact velocity and the mass associated with the cabin floor. The crushing resistance should be such that the maximum stroke is obtained for the design conditions, without permitting a bottoming action.

Finally, the addition of energy absorbing projections or struts extending below the fuselage could serve to reduce the severity of cabin accelerations.

The principles discussed above for providing increased resistance to vertical collapse and lowering acceleration levels for vertical impacts are quite similar to the principles discussed earlier for longitudinal impacts. Therefore, no further discussion of the relative merits of the use of each method is necessary. However, it is important to realize that the principles developed for improving structural crashworthiness, both for longitudinal impacts and for vertical impacts, are applicable in the design of new aircraft as well as in the modification of existing aircraft.

CONCLUSIONS

1. Minor changes in structural design and simple modifications can both yield significant improvement in the basic crashworthiness of aircraft.

2. Improvement in crashworthiness through changes in structural design or modification of existing structure must come either through improvement of the ability of the "protective container" to maintain living space for all occupants during a crash or from reduction of the acceleration levels experienced by the occupants during a crash.

3. Impact environments may be separated into two categories which offer significantly different problems in designing for improvement of crashworthiness.

   In primarily longitudinal impacts, a large percentage of the initial kinetic energy of the aircraft is dissipated in the compression and acceleration of masses of earth and in friction between the aircraft and the earth, and a relatively low percentage of the initial kinetic energy is absorbed by structural deformation.

   In impacts which are primarily vertical, little energy is absorbed by the interaction between the aircraft and the earth. As a consequence, the major portion of the initial kinetic energy of the aircraft must be absorbed by structural deformation.

4. For crashes which occur with primarily longitudinal impact forces, design of new aircraft structures or modification of existing structures to minimize earth scooping can provide large increases in crashworthiness. Use of this method can reduce the magnitude of longitudinal accelerations applied to the aircraft, thereby reducing the level of accelerations encountered by the occupants during a crash. Also, this method can be used to lower the magnitude of forces concentrated on lower forward cockpit (or cabin) structure and, as a result, can reduce localized collapse of the "protective container" in this area.

5. It is possible to predict the locations where fuselage structure is most likely to fail due to compressive buckling in longitudinal impacts. The method presented in this report provides quantitative information which can be used to determine the feasibility of strengthening fuselage structure and upon which modification design can be based.

6. For crashes which occur with primarily vertical impact forces, the improvement of energy absorbing characteristics of the subfloor structure to protect the integrity of main cabin structure, and localized strengthening of upper cabin structure at points where large masses are suspended from upper structure, can greatly increase the ability of the "protective container" to maintain living space for all occupants.

7. Gross aircraft behavior in a crash is subject to analysis using the fundamental principles of mechanics. At present, however, such analysis is hampered by the lack of adequate knowledge of the relationships which apply to determination of the reaction force which decelerates the aircraft upon contact with the ground. The question of how the reaction varies in magnitude with changes in velocity and several questions concerning the mechanisms of energy absorption within the soil, under impact conditions, remain unanswered.

RECOMMENDATIONS

1. It is recommended that a program, in three parts, be established immediately to improve the basic structural crashworthiness of all U.S. Army aircraft:

   a. Investigation of all types and models of present U.S. Army aircraft to develop simple modifications for improving crashworthiness. For fixed-wing aircraft, the effort should be directed first toward reduction of the acceleration levels experienced by the occupants and secondly toward the improvement in the ability of the "protective container" to maintain living space. For rotary-wing aircraft, the initial effort should be directed toward improvement of the energy absorption characteristics of subfloor structure.

   b. Monitoring of all new aircraft designs from the earliest preliminary design stages until the design is finalized to insure that the principles of crashworthy design of basic airframe structure are carefully considered throughout the design.

   c. Periodic reviews of the accident performance of all U.S. Army aircraft, with emphasis on the location of structural weaknesses which degrade the total aircraft crashworthiness, so that design deficiencies may be corrected and so that new developments in technology may be applied without delay.

2. It is also recommended that further investigations be undertaken in the fields of soil dynamics and structural analysis under high-energy impact loading so as to improve the capability of predicting the influences of soil dynamic behavior, initial impact velocity, and structural design details upon the total crash environment. These investigations should have, as a long-range goal, the development of principles and relationships which will allow optimizing aircraft designs for maximum basic crashworthiness.

BIBLIOGRAPHY

1. Avery, J. P., Structural Analysis of Three Crash Impact Configurations in Steel Tube and Fabric Aircraft, TRECOM Technical Report 64-5, U.S. Army Transportation Research Command,* Fort Eustis, Virginia, May 1964.

2. Pesman, G. J., Eiband, A. M., Crash Injury, NASA Technical Note 3775, National Aeronautics and Space Administration, Washington, D.C., November 1956.

3. Preston, G. M., Pesman, G. J., Accelerations in Transport Airplane Crashes, NACA Technical Note 4158, National Advisory Commmittee for Aeronautics, Washington, D.C., February 1958.

4. Braunstein, M. L., Been, R. T., Studies in Accident-Injury Prevention, AvSER 64-1, Aviation Safety Engineering and Research, Phoenix, Arizona, March 1964.

5. Pearson, R. G., Relationship Between Impact Variables and Injuries Sustained in Lightplane Accidents, August 1961, TREC Technical Report 61-95, AvCIR 61-5, U.S. Army Transportation Research Command, Fort Eustis, Virginia, August 1961.

6. Pearson, R. G., Prediction of Degree of Injury from Impact and Damage Variables in Lightplane Accidents, August 1961, TREC Technical Report 61-94, AvCIR 61-1, U.S. Army Transportation Research Command, Fort Eustis, Virginia, August 1961.

7. Rothe, V. E., Turnbow, J. W., Dynamic Crash Test of Fixed-Wing and Rotary-Wing Aircraft as Related to Seat Design, AvCIR Technical Report 62-15, Aviation Crash Injury Research, Phoenix, Arizona, October 1962.

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* Now U.S. Army Aviation Materiel Laboratories.

APPENDIX

EXPERIMENTAL TEST PROGRAM

During the program to develop principles for improving basic structural crashworthiness, three TC-45J twin-engine airplanes were subjected to controlled full-scale crash tests. These tests were designed to provide experimental verification of principles developed during the theoretical investigation that paralleled test work. The three crash tests were conducted by Aviation Safety Engineering and Research (AvSER), a Division of Flight Safety Foundation, Incorporated, at the AvSER full-scale crash test facility located at the Deer Valley Airport, just north of Phoenix, Arizona. The tests were designated T-16, T-19, and T-24, and were conducted 6 November 1964, 22 April 1965, and 12 August 1965, respectively.

Prior to modifications incorporated for the specific objectives of each particular test, the basic structures of all three test airplanes were' identical. The overall objective of the test program, then, was to subject each of the test vehicles to the same severe impact conditions in order to demonstrate the effectiveness of simple structural changes in improving basic aircraft crashworthiness.* The mode of impact chosen for the tests was a wing-low, high-angle-of-impact crash at a velocity approximating initial climb-out and approach speed.

In each test, the airplane was accelerated along a guide rail for a distance of 2000 feet, under maximum power. Test vehicle gross weight at the beginning of the acceleration run was, in each case, approximately 8700 pounds, the maximum gross weight for the aircraft type. See Figures 9, 10, 11.

The desired impact velocity was 90 knots, plus or minus 10 knots. As the aircraft reached the impact area, the following sequence of events occurred:

1. The landing gear and aircraft guidance system hardware were broken free by impact against a prepared barrier, allowing the aircraft to become completely airborne in free flight.

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*Several experiments not directly related to structural crashworthiness were conducted during this experimental test program using the C-45 airplanes as test vehicles. The results of these other experiments are reported elsewhere.
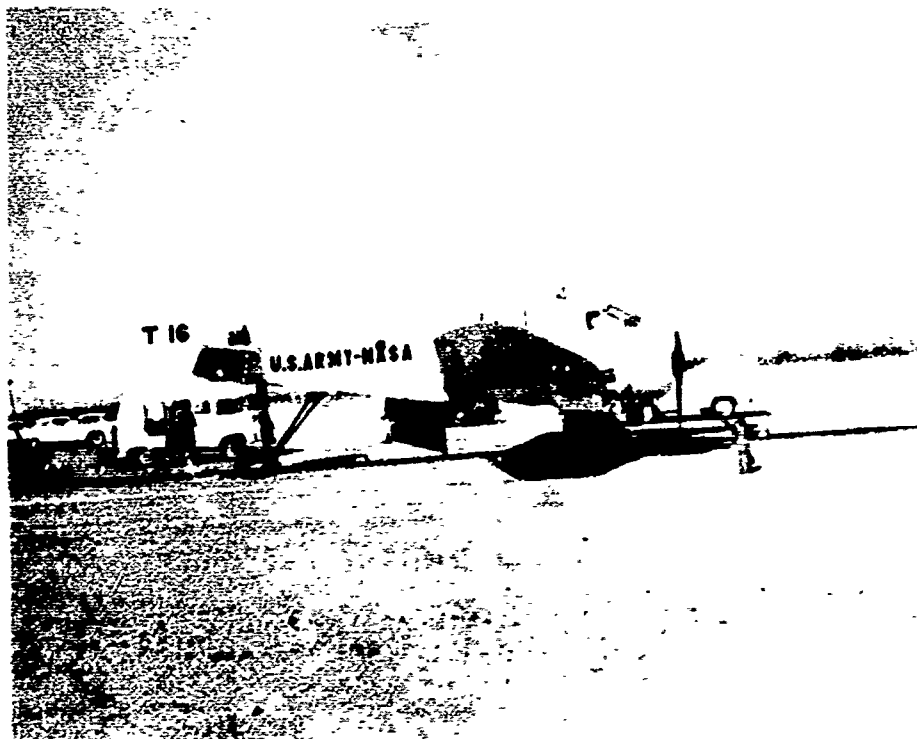
Figure 9. T-16 Airplane, Prior to Crash Test.
(The configuration of this aircraft was
typical of that of all aircraft used in
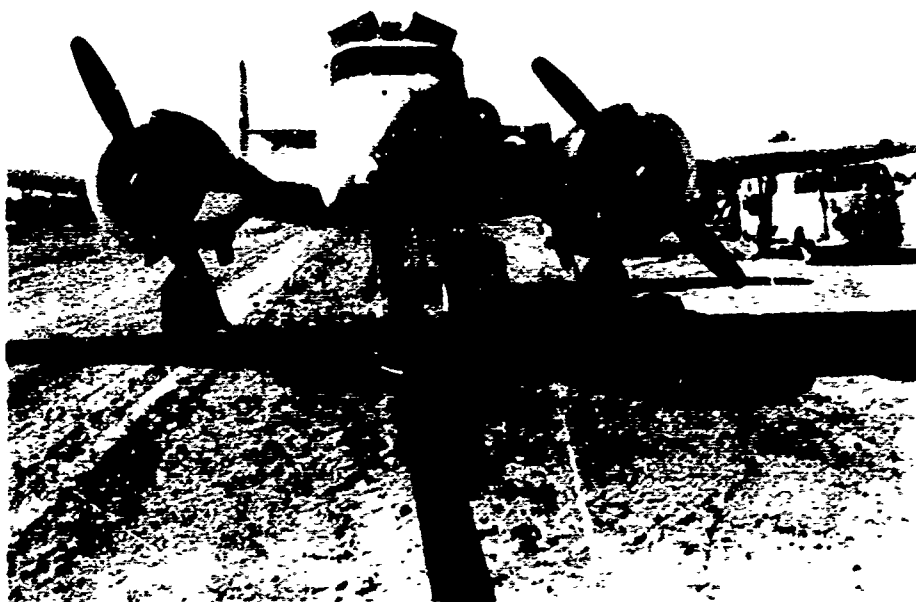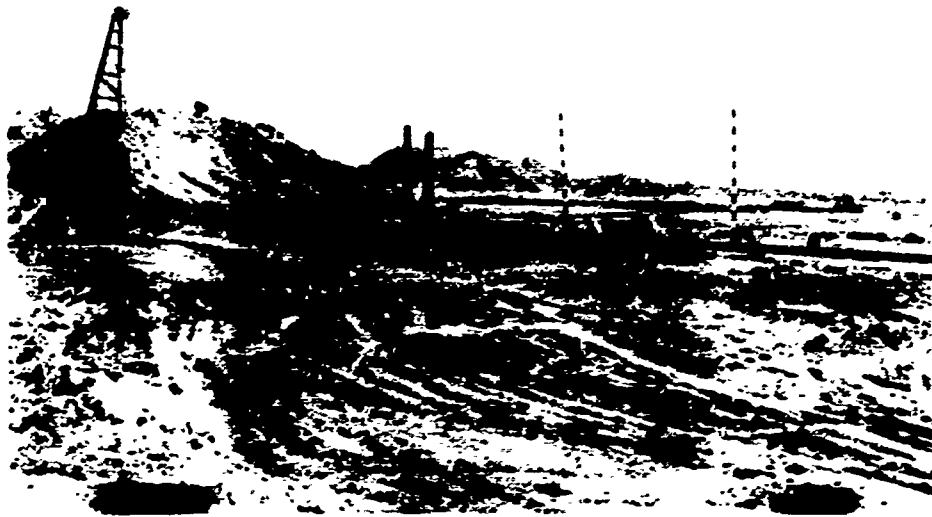this test series.)

Figure 10. Typical Front View of Test Aircraft, Precrash.

Figure 11.   Test Site Viewed From Left, Showing Landing Gear
Barriers, Utility Poles, and Earth Impact Barrier.

2.   The aircraft flew into prepared barriers simulating an impact
with trees with the right wing and a wing-low impact with the
left wing.

3.   The fuselage impacted an earthen barrier designed to produce
severe loading of the occupiable area of the fuselage.

Large wooden utility pole segments, 12 to 16 inches in diameter,
implanted vertically, were used to simulate trees for the right-wing
impacts.

The barrier for the left wing and the fuselage was a compacted earthen
hill constructed at a 35-degree angle to the aircraft flight path, measured
horizontally.   The front surface of this earthen barrier provided a ver-
tical impact angle of 30 degrees, measured along the flight path.

The aircraft guidance system consisted of two guide shoes installed as
shown in Figure 12 to provide positive alignment and control of the test
aircraft.   Both guide shoes completely enveloped the top of the guide rail,
providing both vertical and lateral support and guidance for the aircraft.
Engine power was set manually prior to release of the aircraft for the
acceleration run, with a radio link command system provided to shut
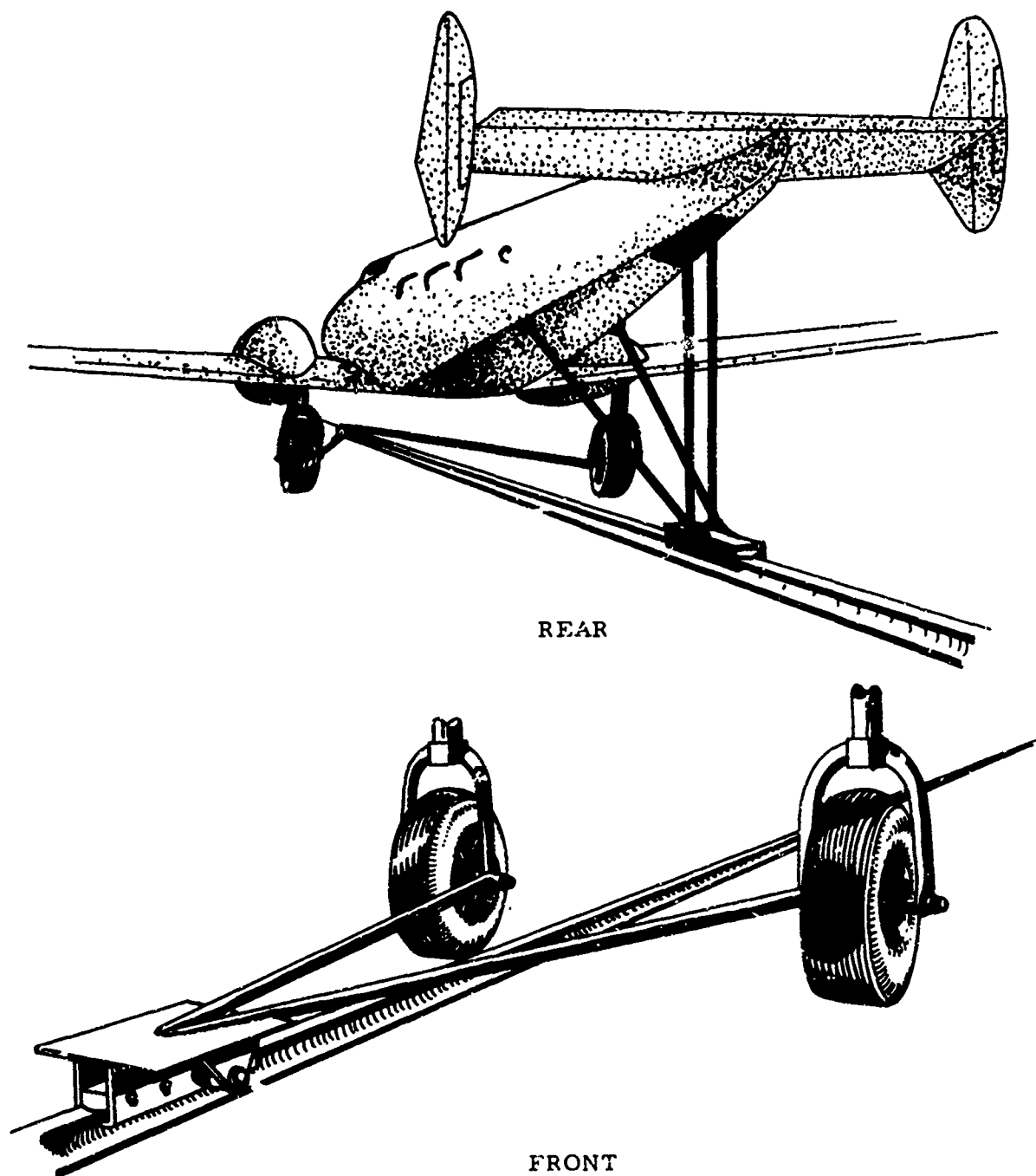down the engines if it became necessary to abort any test.

REAR

FRONT

Figure 12. Aircraft Guidance System - Front and Rear Views.

Electronic transducers were placed aboard the test vehicles at locations
where measurement of forces or accelerations was required. The sig-
nals obtained from the transducers were recorded by an 82-channel
magnetic tape recording system installed in the test aircraft. Each com-
ponent of the magnetic tape recording system was designed to record
accurate and reliable data under the severe environment of a crash.
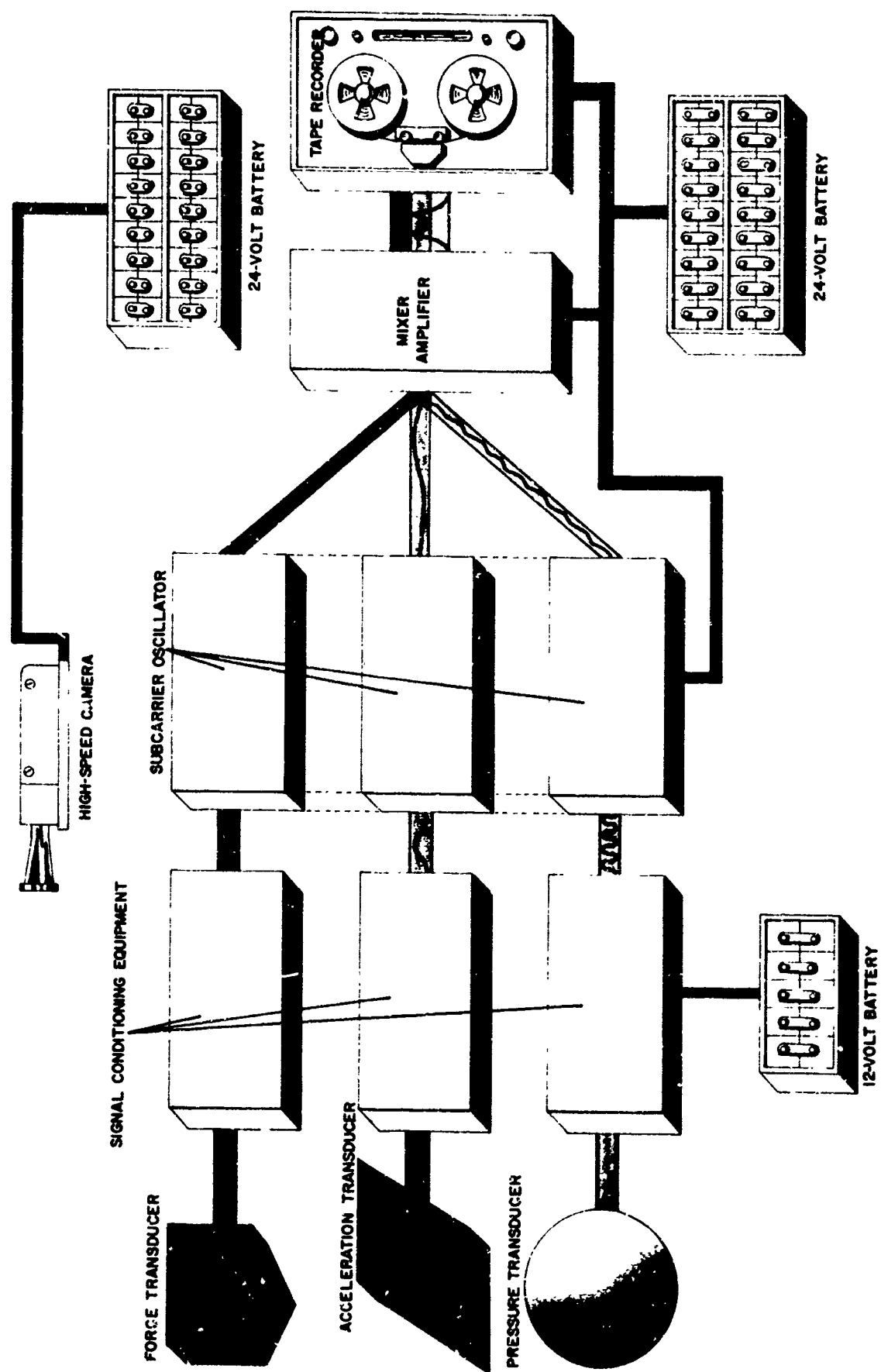The data recording system is illustrated schematically in Figure 13.

Figure 13.   Onboard Instrumentation System.

The major components of the recording system, including the signal conditioning equipment, the subcarrier oscillators, the mixer amplifier, the magnetic tape recorder, and associated battery power supplies, were contained in a protected box mounted at the rear of the passenger section of the fuselage. This location was chosen as the least likely to be damaged during the crash. Shielded cables connected the transducers to the recording system.

The photo instrumentation consisted of high-speed motion picture cameras installed aboard the test aircraft and both high-speed and normal-speed motion picture cameras photographing the impact from ground positions around the impact site (Figure 14). Still photographs were taken before and after the crash.

Photosonics 16mm-1B high-speed cameras were used in all onboard installations. These cameras have been used many times for onboard photography during very severe impact conditions and have proven to be very rugged and reliable.

At ground camera locations, the cameras used were the Photosonics 16mm-1B, described above, the Bolex H-16mm, Bell and Howell Model 70, both 16mm and 35mm, and the Traid 200 Fotoscorer.

Correlation between the several channels of recorded electronic data and the motion pictures was accomplished by automatically closing a circuit to fire flashbulbs located in the field of all cameras and recording the firing signal as data on the magnetic recording system. Timing was provided for the magnetic recording system by a 100-cycles-per-second square-wave oscillator, the output of which was recorded as data. Photographic data timing was provided by photographically recording light pulses of known frequency on the edges of film as it passed through the cameras.

T-16 TEST OBJECTIVES

T-16, the first of the series of three tests, was conducted without modification of the basic structure of the test vehicle to provide base-line data for use in determining the effectiveness of structural changes to be made in succeeding tests for improving crashworthiness. Accordingly, the primary objectives of the experiment were:

1. To obtain the time histories of fuselage longitudinal, vertical, and lateral accelerations at several locations along the fuselage, including the center of gravity.
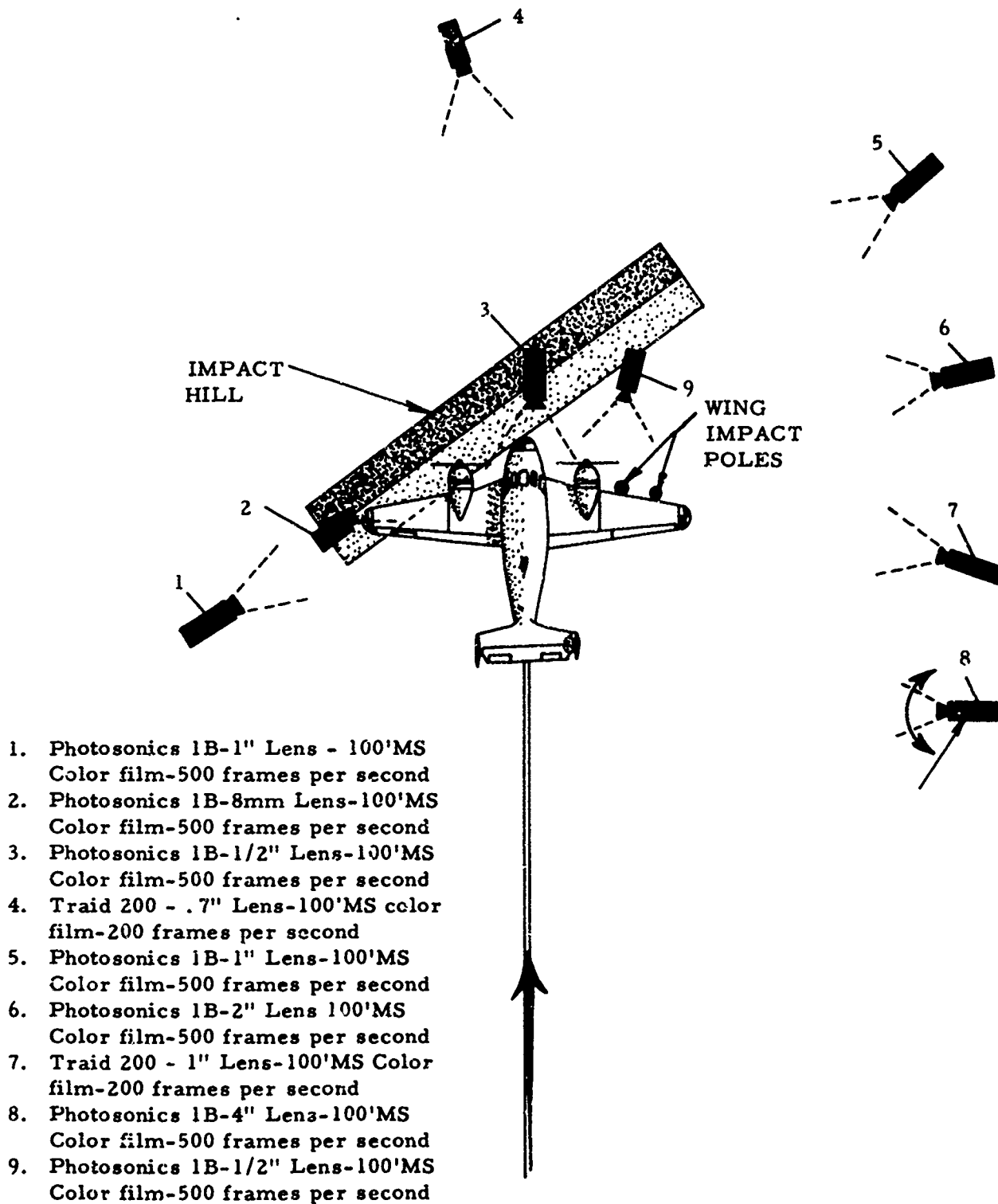
IMPACT
HILL

WING
IMPACT
POLES

1. Photosonics 1B-1" Lens - 100'MS
Color film-500 frames per second
2. Photosonics 1B-8mm Lens-100'MS
Color film-500 frames per second
3. Photosonics 1B-1/2" Lens-100'MS
Color film-500 frames per second
4. Traid 200 - .7" Lens-100'MS color
film-200 frames per second
5. Photosonics 1B-1" Lens-100'MS
Color film-500 frames per second
6. Photosonics 1B-2" Lens 100'MS
Color film-500 frames per second
7. Traid 200 - 1" Lens-100'MS Color
film-200 frames per second
8. Photosonics 1B-4" Lens-100'MS
Color film-500 frames per second
9. Photosonics 1B-1/2" Lens-100'MS
Color film-500 frames per second

Figure 14.   Ground Camera Locations.

2.   To observe the pattern and the severity of structural defor-
mations, noting especially deformations which had an important
effect on occupant living space or cabin energy absorption
requirements.

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To collect the data necessary for meeting these objectives, the following measurements were recorded.

1. Forward-fuselage (cockpit) acceleration, longitudinal
2. Forward-fuselage (cockpit) acceleration, vertical
3. Forward-fuselage (cockpit) acceleration, lateral
4. Mid-fuselage (c. g.) acceleration, longitudinal
5. Mid-fuselage (c. g.) acceleration, vertical
6. Aft-fuselage acceleration, longitudinal
7. Aft-fuselage acceleration, vertical
8. Aft-fuselage acceleration, lateral

Photographic data, along with postcrash observations, provided information concerning the pattern and severity of structural deformations. See Figures 15 through 21.

TEST RESULTS AND ANALYSIS

This test successfully met all objectives, reaching the general goals which were common to all crashworthiness experiments and also meeting the specific requirements of this test.

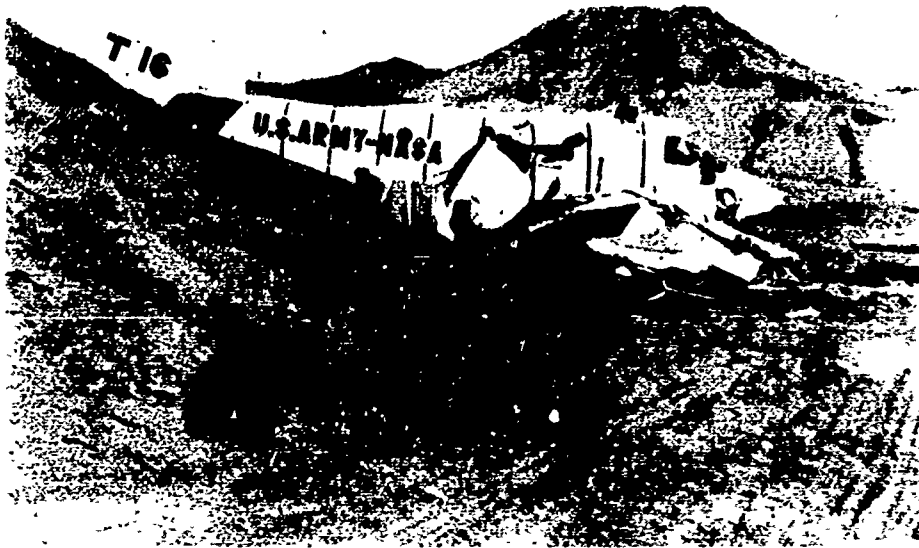Figure 15. Aerial View of T-16 Vehicle Immediately Following Crash.

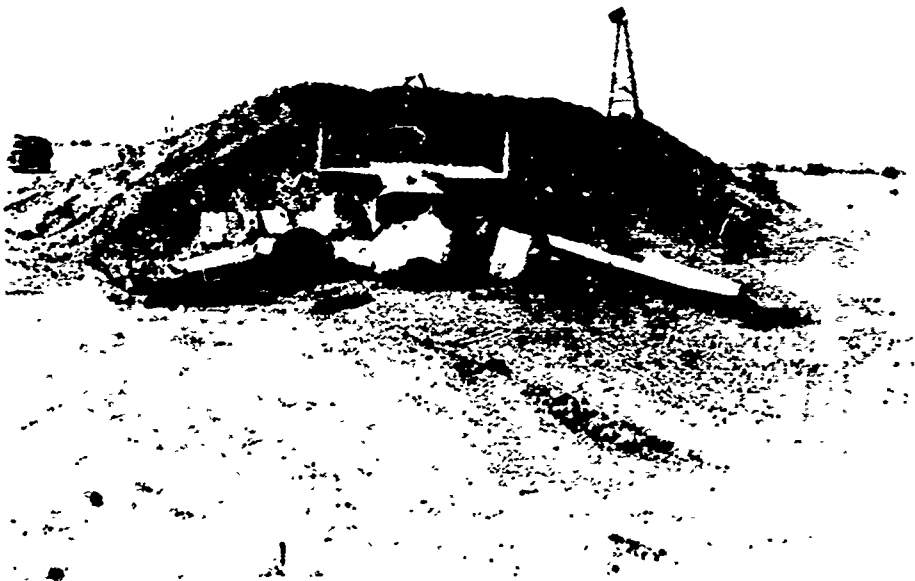Figure 16. Right-Side View of T-16 Vehicle, Postcrash.

Figure 17. Front View of T-16 Vehicle, Postcrash.

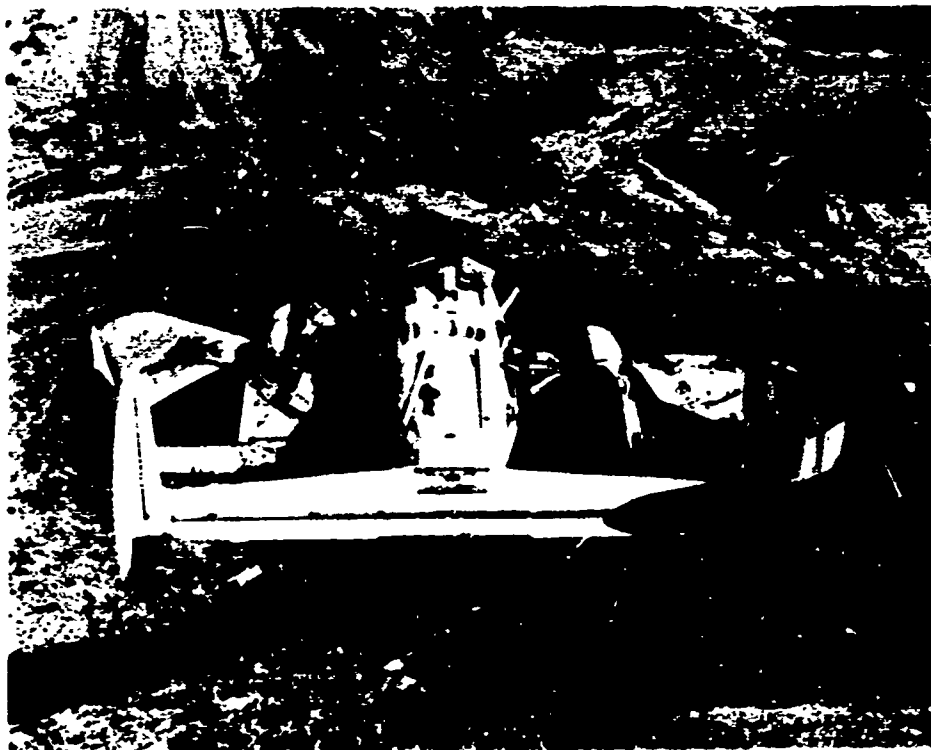Figure 18.   Left-Side View of T-16 Vehicle, Postcrash.

Figure 19.   Aft View of T-16 Vehicle, Postcrash.

Figure 20. View of Cockpit Area of T-16 Vehicle, Showing Buckling of Side Structure Caused by Aft Forces on Forward Cockpit Bulkhead.
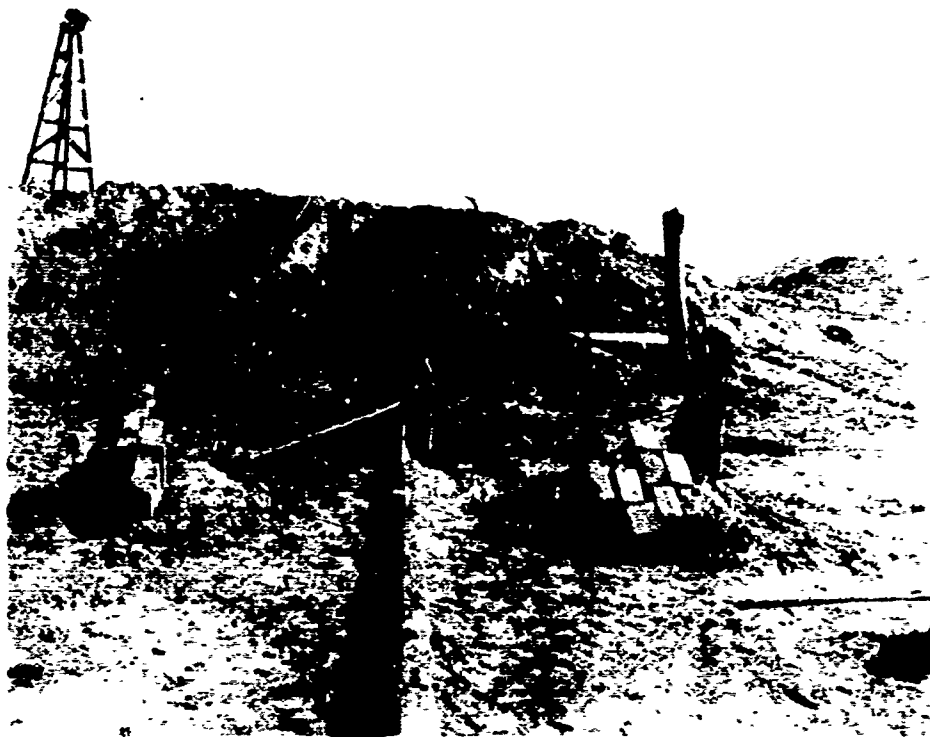

Figure 21. Gouge Marks on Face of Earth Impact Barrier Following T-16.

The aircraft struck the landing gear barriers with an initial velocity of 84 knots. The main landing gear failed immediately, placing the aircraft in free flight. The aircraft then struck the two barrier poles (simulating trees) with the right wing and the earth barrier with the left wing. The wing impacts were immediately followed by impact of the aircraft nose against the earth barrier.

The crash which resulted from this sequence of impact events was severe. Large structural deformations occurred, yet the occupiable part of the airplane was not totally destroyed. It appears that the next degree of crash severity would have been complete collapse of cabin structure, resulting in an unsurvivable crash injury environment.

The nose structure, forward of the forward cockpit bulkhead, collapsed immediately upon impact. This structure snapped inward instead of crushing, which allowed the lower forward cockpit structure to contact the earth barrier. This resulted in excessive longitudinal loading and partial collapse of the forward cockpit and in considerable reduction in the overall survivability in the cockpit.

As the fuselage pitched up during the crash, the fuselage bent upward and the upper fuselage structure buckled, at approximately fuselage station 180. This buckling, which was due to excessive compressive loading of this upper structure, resulted in only a very small loss of occupiable space within the cabin. However, had impact energy been only slightly higher, the damage would have been much more severe and occupant survival would have been more greatly affected.

Analysis of motion pictures and recorded electronic data shows that impact with the wing and fuselage barriers produced a single primary impact. During this impact, longitudinal velocity was reduced from approximately 144 feet per second to 40 feet per second in 0.22 second. The maximum longitudinal accelerations were 77G measured in the cockpit, 66G measured at the center of gravity, and 28G measured in the aft cabin.

The vertical acceleration pulse was shorter in duration than the longitudinal pulse, lasting for approximately 0.16 second. The highest vertical acceleration, 36G, was measured at the cockpit floor. The magnitude of vertical acceleration decreased aft of the cockpit within the passenger cabin, as would be expected, considering the angular acceleration encountered.

Lateral accelerations were also highest in the cockpit, approximately 20G in each direction, and decreased aft of that point.

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Figures 22 through 29 show acceleration measurements recorded during the test.
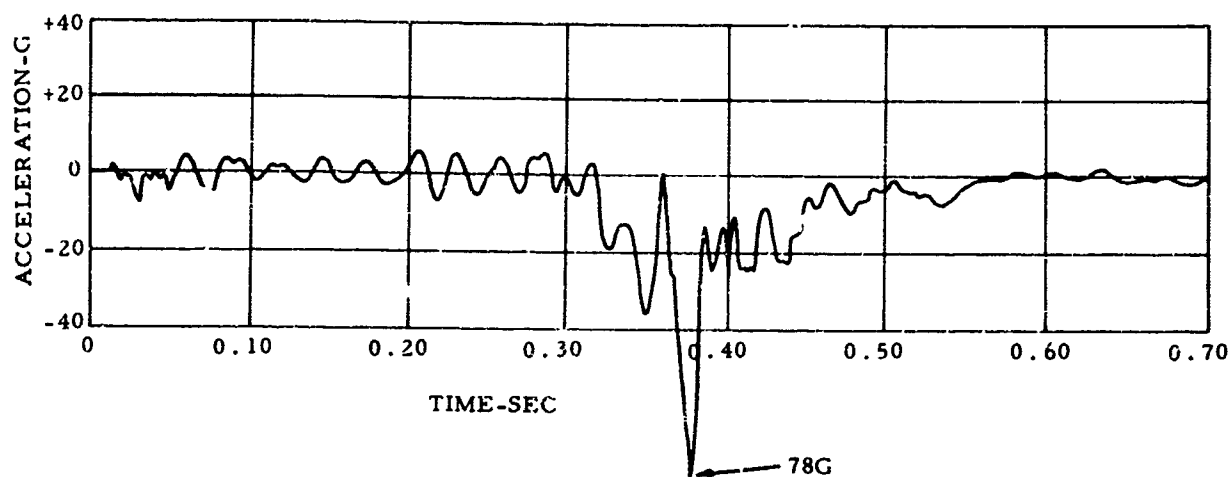

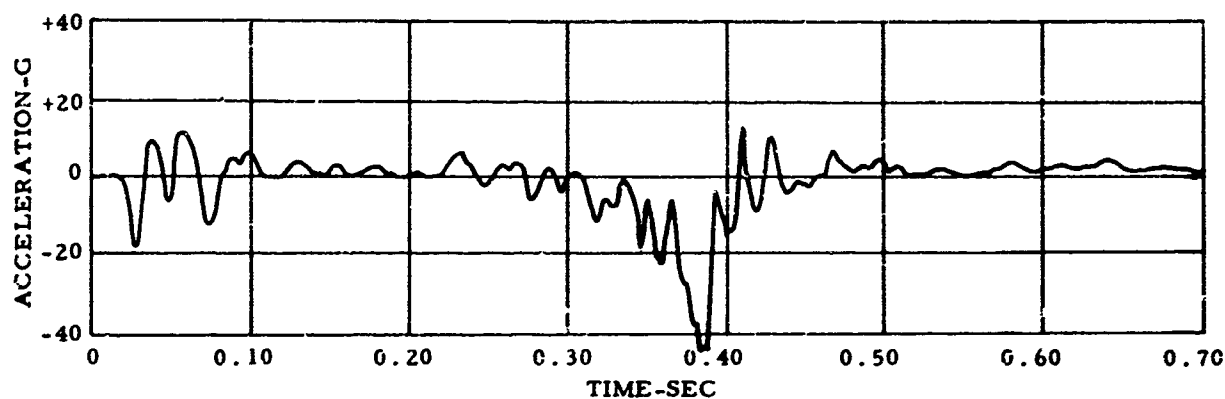
Figure 22. T-16 Cockpit Acceleration, Longitudinal.

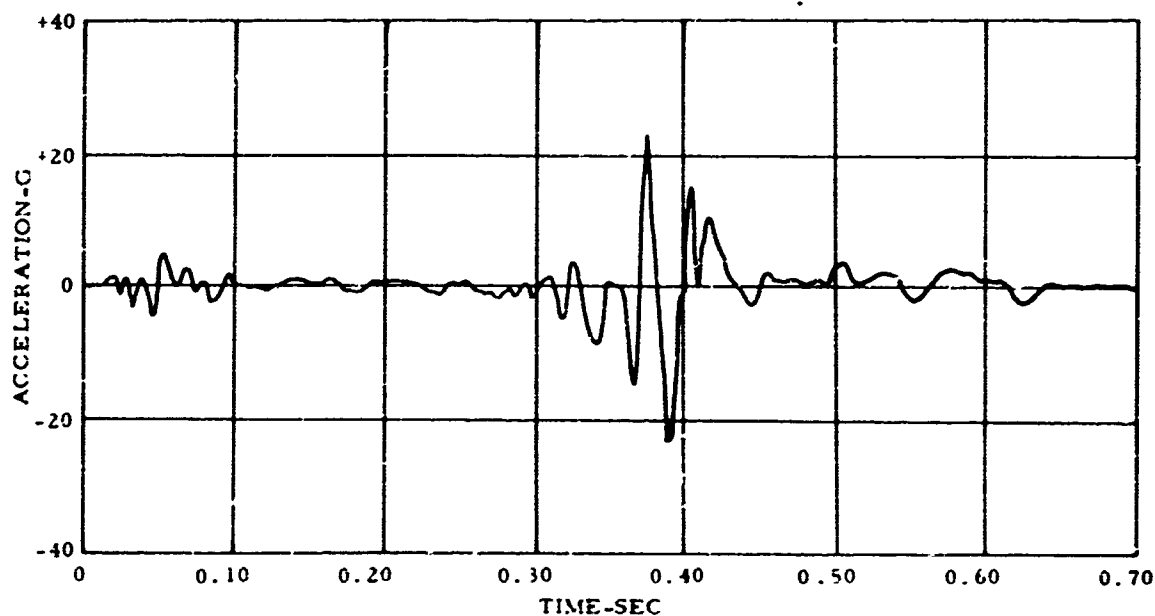Figure 23. T-16 Cockpit Acceleration, Vertical.
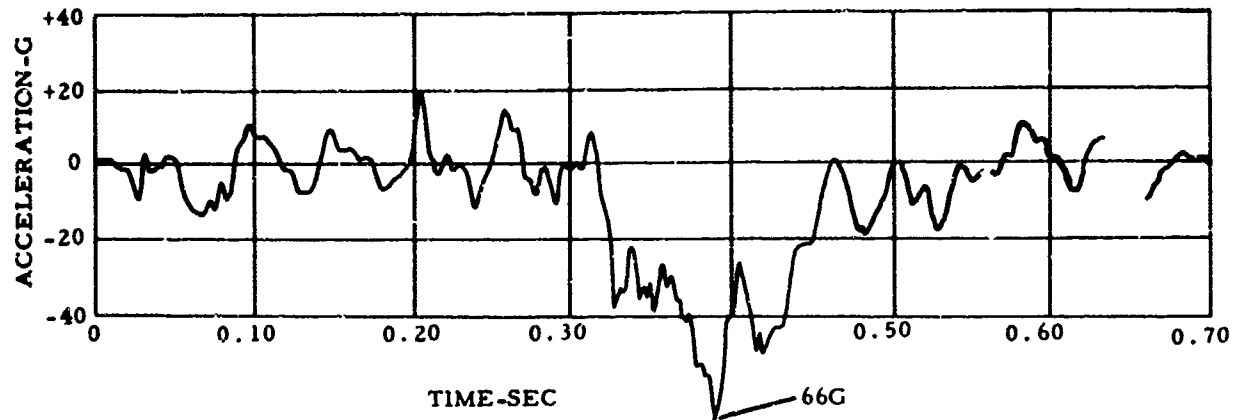

Figure 24. T-16 Cockpit Acceleration, Lateral.

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Figure 25. T-16 Mid-Cabin (c. g.) Acceleration, Longitudinal.
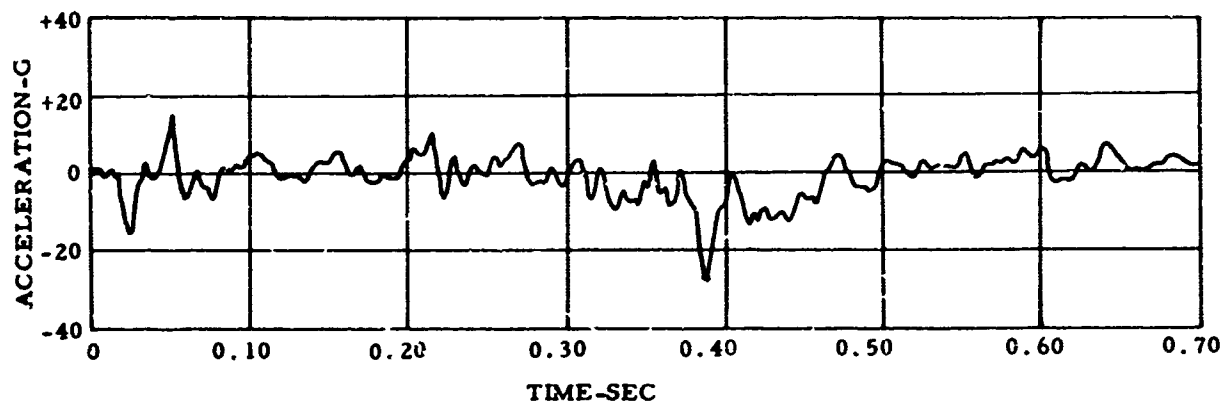

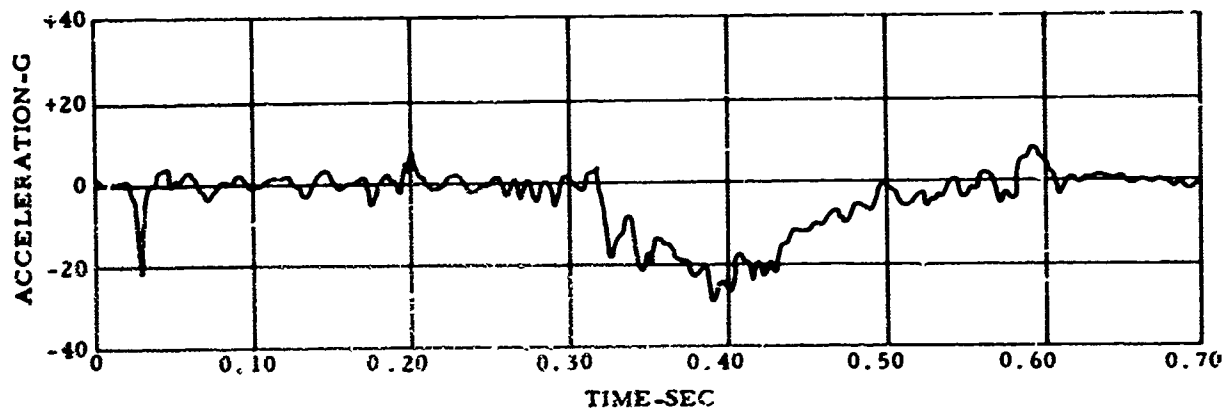Figure 26. T-16 Mid-Cabin (c. g.) Acceleration, Vertical.

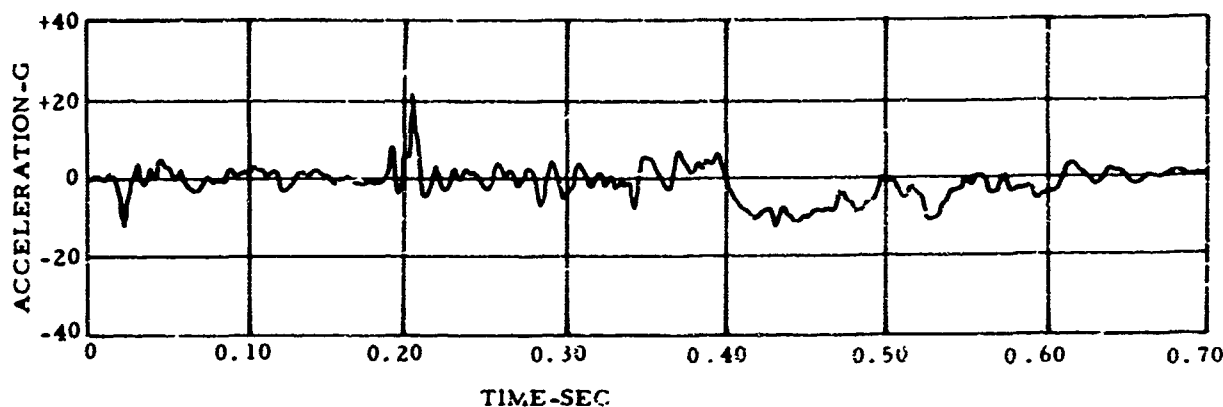Figure 27. T-16 Aft-Cabin Acceleration, Longitudinal.

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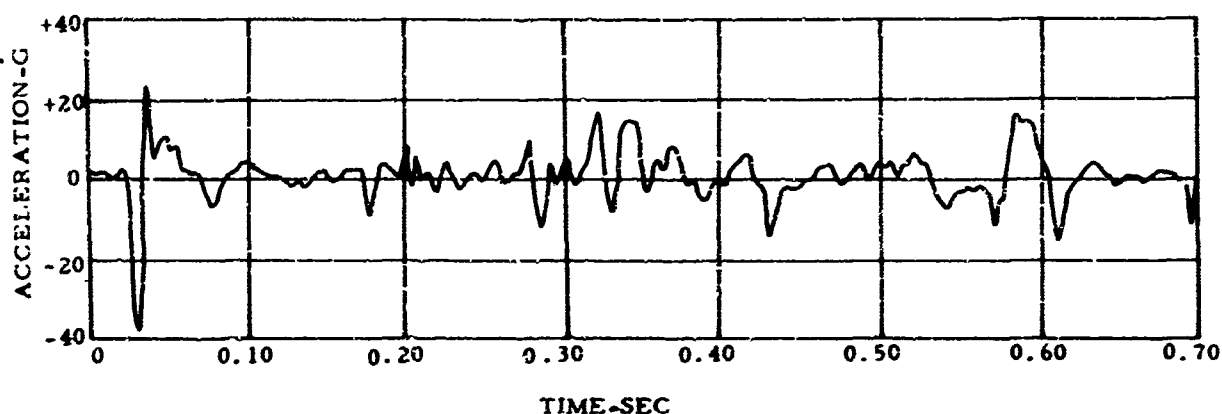Figure 28. T-16 Aft-Cabin Acceleration, Vertical.

Figure 29. T-16 Aft-Cabin Acceleration, Lateral.

Further analysis of the motion pictures shows that from initial impact until 0.16 second after initial impact, the aircraft nose was digging into the barrier and large masses of earth were being impulsively accelerated. Postcrash investigation revealed deep gouges on the face of the barrier, (Figure 21) showing where the nose and left engine dug into the hill.* Also, at the end of this 0.16-second period, the aircraft had rotated 30 degrees in pitch and was sliding along the face of the hill. Figure 30 presents a longitudinal velocity-time diagram for T-16.

Postcrash investigation revealed further evidence of the severity of the crash forces. Dummies placed in the pilot's and copilot's seats were displaced forward greatly, and their heads had contacted the instrument panel (which had moved aft due to local structural collapse). The cockpit

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*The left wing separated from the aircraft approximately 0.05 second after initial impact: consequently, the effect of the left engine gouging was small in terms of velocity decrease.
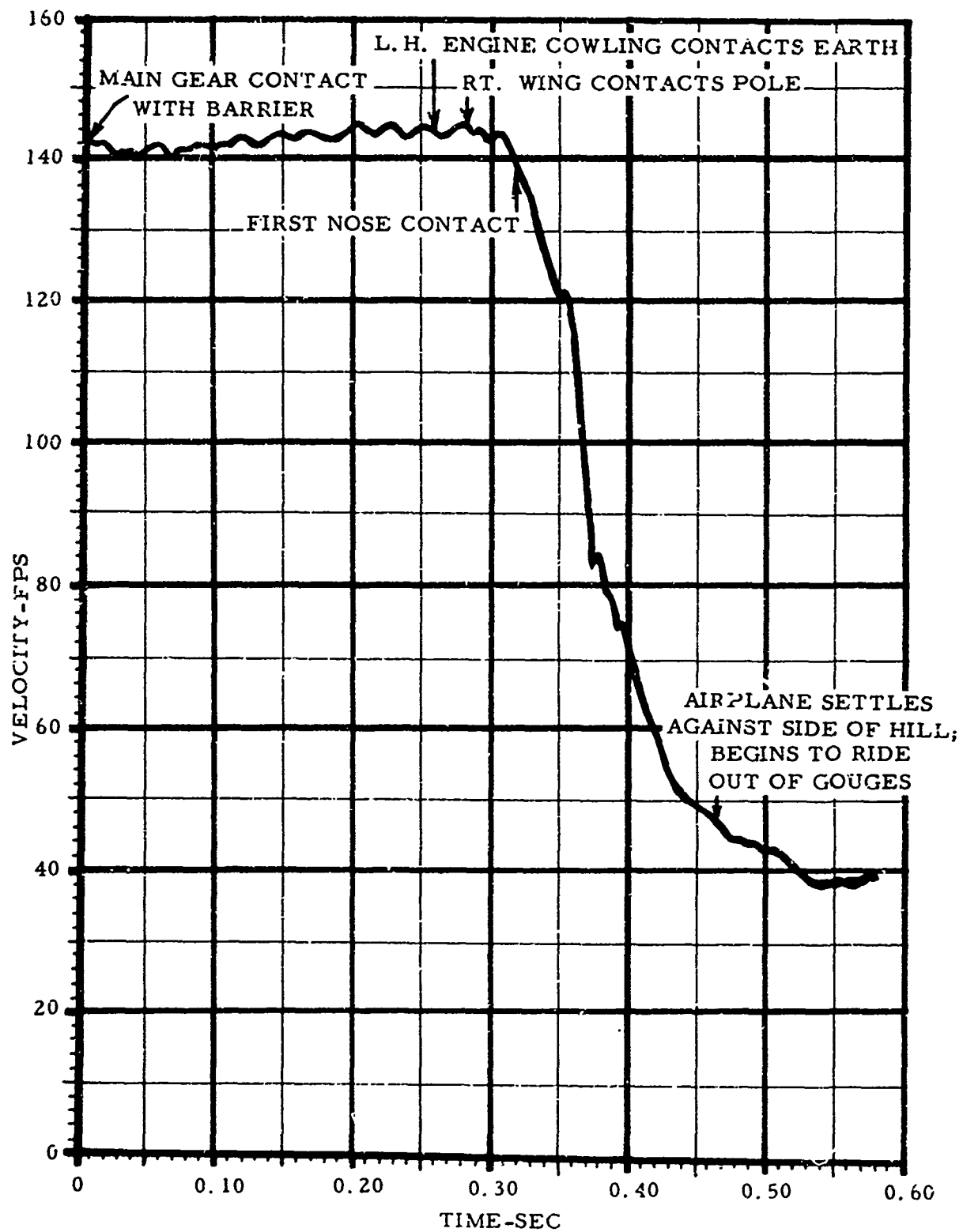
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Figure 30.   T-16 Longitudinal Velocity - Time Diagram.
(Beginning at gear impact - cockpit accelerometer).

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seats were bent forward due to the restraint harness loads. The lower forward cockpit bulkhead was also pushed aft, and the dummies' feet were trapped between the rudder pedals and the floor.

Study of the results of T-16 yielded the conclusion that the initial effort to improve the basic structural crashworthiness of the C-45 should be directed toward modification of the lower nose structure to prevent snap-in failure during impact, to provide a skidding surface, and to reduce earth scooping.

T-19 TEST OBJECTIVES

T-19 was the second of the series of three tests. Conditions of T-19 were intended to duplicate the conditions of T-16 as closely as possible. For this test, however, the lower nose structure was modified to prevent snap-in failure.

The primary objective of this test was to determine the effectiveness of the nose modification in reducing earth scooping and in reducing the severity of the crash environment.

In order to accomplish this objective, instrumentation was installed to measure

1. Cockpit acceleration, longitudinal
2. Cockpit acceleration, vertical
3. Cockpit acceleration, lateral
4. Mid-fuselage (c.g.) acceleration, longitudinal
5. Mid-fuselage (c.g.) acceleration, vertical
6. Mid-fuselage (c.g.) acceleration, lateral
7. Aft-cabin acceleration, longitudinal
8. Aft-cabin acceleration, vertical
9. Aft-cabin acceleration, lateral

In addition, photographic coverage was provided to record structural deformations with a high-speed motion picture camera placed so as to obtain more detailed information concerning the nose impact than had been obtained from T-16.

The modification of the nose structure of the aircraft consisted of the reinforcement of the nose formers at fuselage stations 19.88 and 29.12 and the addition of a partial bulkhead at fuselage station 38.38. The reinforcements and the new bulkhead consisted of a web of bare 2024-T3 aluminum alloy, 0.032 inch thick, reinforced with vertical stiffeners and caps made from 1-inch by 1-inch by 1/8-inch 6061-T6 aluminum

angle, as shown in Figures 31, 32, and 33. The vertical stiffeners and cap angles were riveted to the webs using 3/32-inch-diameter aluminum rivets. The webs were then attached to the aircraft by riveting to existing frames, or by riveting to small clips where frames were not present. The effect of nose modification was to provide three additional partial bulkheads to prevent snap-in of the lower nose during impact, to provide a skidding surface. Figures 34 and 35 show the nose structure of T-19 before and after modification.

Total weight of the material added to modify the structure was 8 pounds.

Other preparations for T-19, including the test site preparation, were essentially the same as preparations made for T-16.
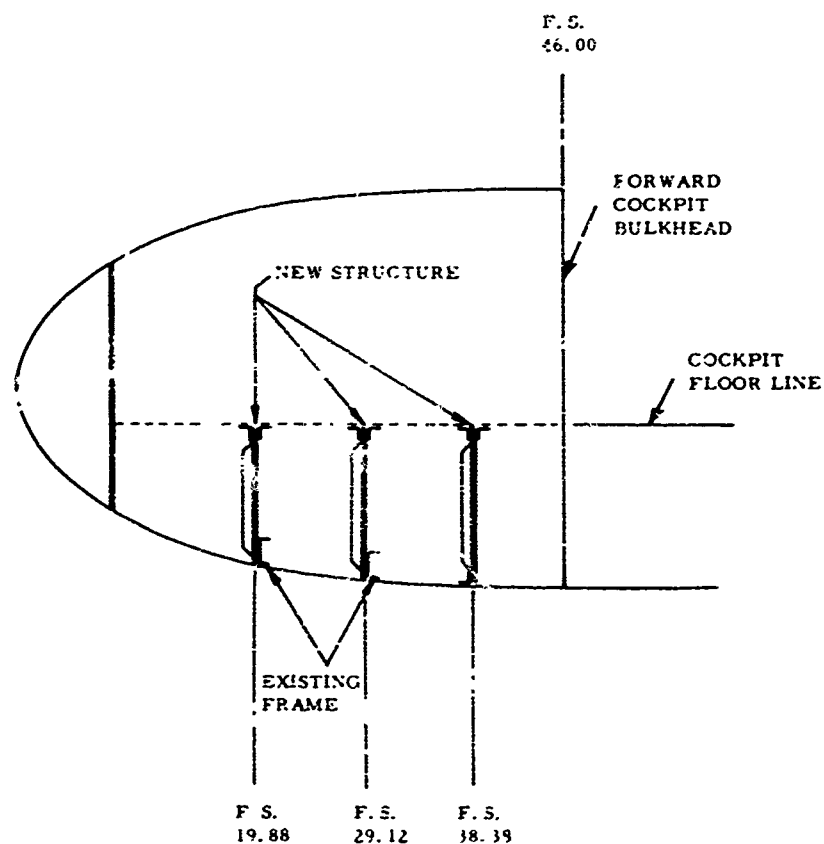
Figure 31.   Sketch of Locations of Nose Structural
Reinforcements (Side View).

WEB CAPS
(TYPICAL)
1 IN. x 1 IN. x 1/8 IN.
AL ANGLE

40 IN.

9 IN. 9 IN.

9-1/4 IN. 10-3/16 IN.

0.032 IN. AL WEB
(TYPICAL)

VERTICAL
STIFFENERS
(TYPICAL)
1 IN. x 1 IN. x 1/8 IN.
AL ANGLE

CONTOUR TO FIT INSIDE
SKIN LINE AT F. S. 38.38
(TYPICAL)

FUSELAGE STATION 38.38 REINFORCEMENT
(THIS MEMBER ATTACHED TO AIRCRAFT LOWER SKIN USING 24
ATTACHMENT CLIPS, EQUALLY SPACED)

34-1/2 IN.

7 IN. 15-1/2 IN.
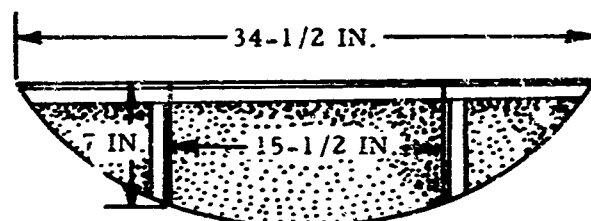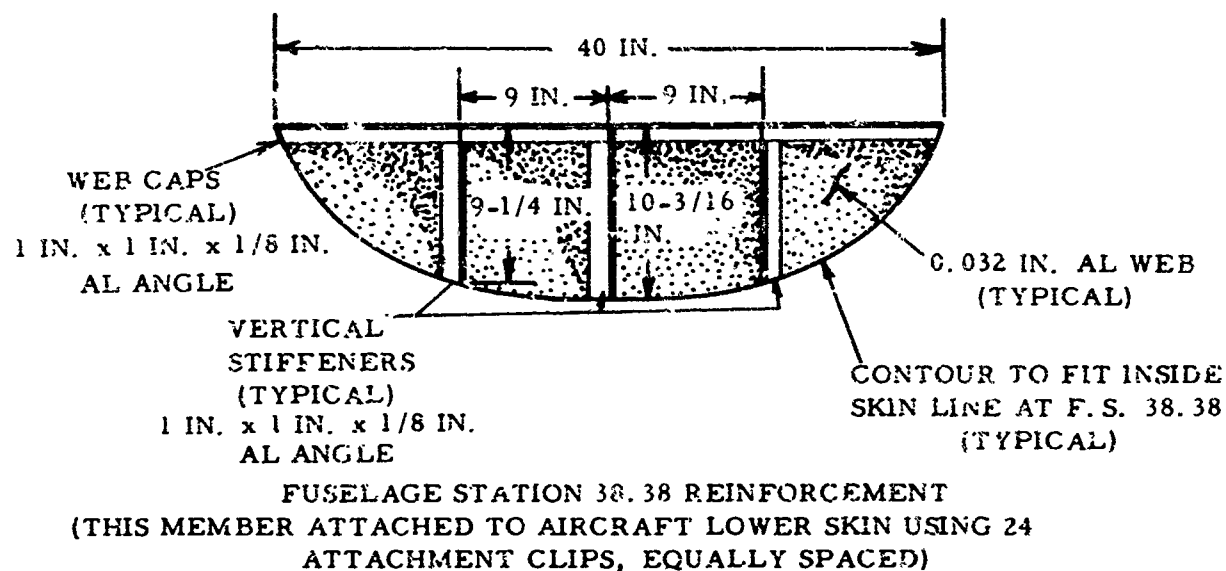
FUSELAGE STATION 29.12 REINFORCEMENT
(THIS MEMBER ATTACHED DIRECTLY TO EXISTING FRAME)

22 IN.

11-3/8 IN.

5-1/2 IN.
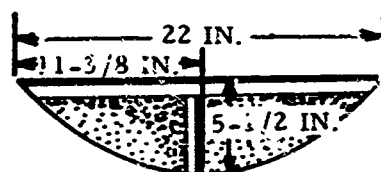
FUSELAGE STATION 19.88 REINFORCEMENT
(THIS MEMBER ATTACHED TO EXISTING FRAME, WITH
9 CLIPS USED WHERE FRAME DID NOT EXTEND
ACROSS LOWER SKIN)

Figure 32. Sketches of Nose Structure Reinforcement
Webs and Stiffeners.

TYPICAL RIVET SPACING PATTERN FOR ATTACHMENT OF CAPS
TO REINFORCING WEBS.

Figure 33.   Attachment of Cap Angle to Webs and Existing Frames.

Figure 34.   Nose Structure of T-19 Airplane Prior to Modification.

Figure 35. Nose Structure of T-19 Aircraft After Modification.

TEST RESULTS AND ANALYSIS

T-19 was successful in meeting the desired impact objectives. Initial
impact velocity was approximately 140 feet per second, which was very
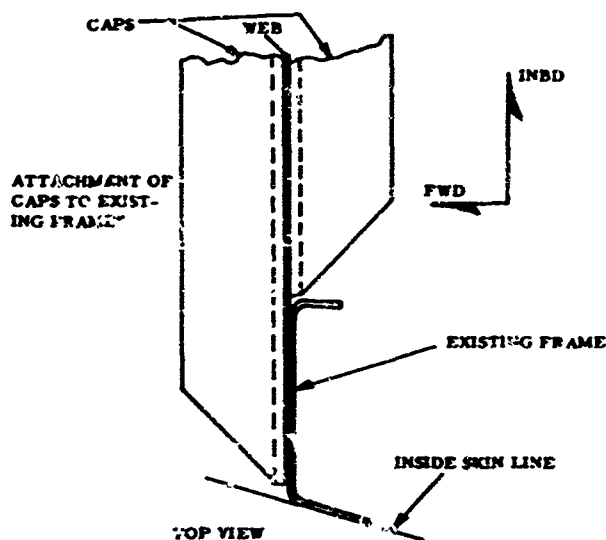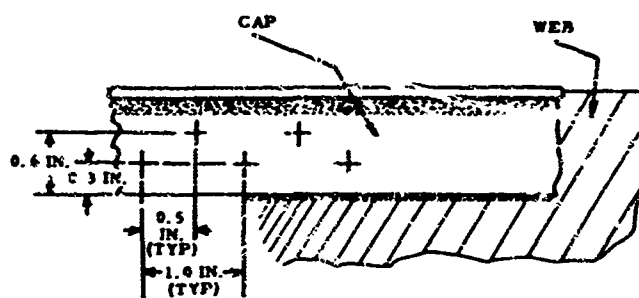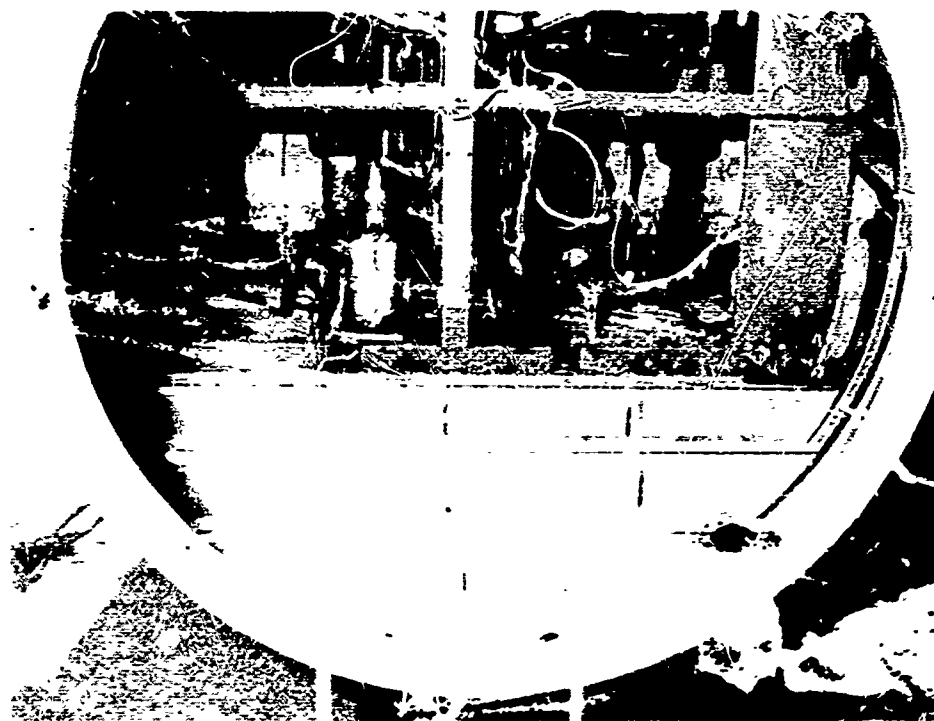near the 144 feet per second velocity attained in T-16. All photographic
equipment operated properly. The electronic data recording system,
however, was unsuccessful. Due to extreme electronic interference, the
recorded data was of such poor quality that analysis was not possible.

Postcrash investigation and analysis of motion pictures allowed adequate
analysis of the behavior of the aircraft during the test, however.

The aircraft struck the barrier in the same manner as did the T-16 air-
craft. During this impact, the empennage separated from the forward
fuselage at the body frame just forward of the tail wheel (fuselage station
341). The empennage section rotated to the left and came to rest be-
neath the aft fuselage section.

Also, during the primary impact both wings were broken off the air-
craft. The left-wing outer panel came to rest past the top of the hill,
even with the cockpit section of the aircraft, while the right-wing outer
panel came to rest near the pole barriers on the face of the hill. Both
engines broke free and came to rest just forward of the nose of the air-
craft. Figures 36 through 39 show postcrash conditions of T-19.

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Figure 36.   T-19 Vehicle. Postcrash, Showing Lower
Nose Structural Damage.

Figure 37.   Left-Side View of T-19 Vehicle, Postcrash.

Figure 38. T-19 Vehicle, Postcrash, Quartering
Right-Aft View.

Figure 39. Quartering Left-Aft View of T-19 Vehicle, Showing
Buckling of Upper Fuselage Structure.

The nose modification was effective in preventing the earth gouging. The lower nose structure was crushed to a flat surface, but it did not snap in and did not dig into the ground to any appreciable extent.

Motion picture analysis revealed that the aircraft velocity was reduced from 140 feet per second to approximately 62 feet per second during the primary impact, which lasted approximately 0.20 to 0.25 second. This indicates that the primary longitudinal impact pulse accounted for much less energy loss in T-19 than in T-16. Since the duration of the pulse in T-19 was approximately the same as the duration of the primary pulse in T-16, it is concluded that the longitudinal acceleration was lower in T-19.

Pitch change in T-19 occurred during approximately the same time period, 0.15 second to 0.18 second, as in T-16. Therefore, it is concluded that vertical accelerations occurred which were of the same order of magnitude as those which were measured in T-16.

Although longitudinal accelerations were lower than those measured in T-16, the top of the fuselage buckled during this test also. The failure, which was less severe than the T-16 buckling, occurred at approximately fuselage station 140. The upper structure aft of this location was reinforced by the instrumentation tape recorder package installation.

The results of T-16 and T-19 indicate that the strength of the upper fuselage structure should be improved prior to the next test to increase the impact velocity at which cabin collapse begins and hence to improve the crashworthiness of the aircraft.

T-24 TEST OBJECTIVES

General preparations for T-24 were the same as preparations made for earlier tests. The test site was prepared in the same way as that for T-16 and T-19, and general aircraft preparations were equivalent to the work done earlier.

The primary objective of this test was to determine the effectiveness of increasing upper cabin compressive strength in reducing cabin collapse due to fuselage bending associated with rapid pitch up for longitudinal crashes. For this test the structural reinforcement used for mounting the instrumentation package was extended longitudirally to provide additional strength in the area which had failed in earlier tests. The strength of the members used for the modification was more than adequate, because of the requirements imposed by the attachment of the

instrumentation package, therefore, weight of the modification, as made, is not applicable.

The nose structure of the T-24 aircraft was modified in the same way as that for T-19.

TEST RESULTS AND ANALYSIS

T-24 did not successfully meet its crashworthiness objectives, for two reasons. First, the test vehicle sustained partial engine failure during the acceleration run, and initial impact velocity was only approximately 60 knots, which is much below both the desired velocity of 90 knots and the velocity attained during the two previous tests, approximately 85 knots. As a result of this lower impact velocity, the kinetic energy of impact was entirely absorbed by wing deformations and failure of engine mounts. The fuselage sustained little structural deformation (Figures 40 through 43). For this reason, the experiment to determine the effectiveness of upper fuselage modification was inconclusive.

Figure 40. Right-Side View of T-24 Vehicle Resting on
Earth Impact Barrier.

Figure 41. Quartering Left-Aft View of T-24 Vehicle.

Figure 42. Nose of T-24 Vehicle, Side View.

Figure 43. Nose of T-24 Vehicle, Front View.

Second, the electronic data recording system was damaged during the impact, and the data obtained were unreliable.

The conclusion, then, must be that T-24 was not successful as a structural crashworthiness experiment. It should be noted, however, that other experiments aboard the test vehicle were highly successful, since their success did not depend primarily upon impact energy cr collection of acceleration and force data.

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13. ABSTRACT

The area of crash behavior analysis of aircraft structures is investigated. The investigation begins with the definition of two indices of crashworthiness of basic aircraft structures and the analysis of the influence of several general types of structural modifications upon these two indices. This analysis, using fundamental principles of mechanics, contains several simplifying assumptions, which are explained as they are introduced. Design concepts to improve the ability of the "protective container" to maintain living space for occupants during a crash or to attenuate the accelerations experienced by occupants during a crash are developed for crash conditions which are either primarily longitudinal in nature or primarily vertical in nature. Analytical methods are then provided to show how and when to apply these design concepts to any particular aircraft. The principles which are presented are suitable for use during design of new aircraft as well as modification of existing aircraft. The results are presented from three full-scale crash tests of small twin-engine airplanes which were conducted as a part of this investigation.

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